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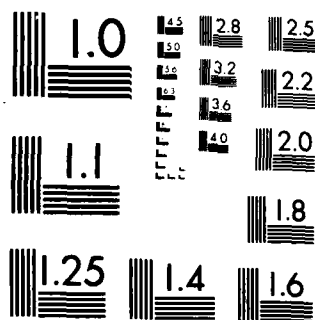
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PHYSICAL OCEANOGRAPHY PROGRAM

(ONR CODE 1122PO)

PROGRAM SCIENCE ABSTRACTS

AD-A174 019

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19. ABSTRACT (Continue on reverse if necessary and identify by block number) This report presents a summary of work sponsored by the Physical Oceanography Program, (Code 1122P0), Office of Naval Research, Environmental Sciences Directorate, covering the FY85 period. It includes brief descriptions of research for about 110 physical oceanography projects, and a bibliography containing publications in FY85 supported by the Program.							
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FORWARD

This report, published annually, is a compilation of abstracts submitted by the principal investigators supported by the Physical Oceanography Program (Code 1122P0). The abstracts describe projects supported in FY85. This year, a bibliography is included. It lists publications supported wholly or in part by the Program that appeared between 1 October 1984 and 30 September 1985.

The report is intended to communicate the diversity and scope of the physical oceanography effort. We appreciate any comments concerning the research, or this publication. We also encourage contacts directly with the scientists themselves, and have provided addresses and phone numbers for that purpose. Programmatic questions should be addressed to the 1122P0 staff (listed below).

Acknowledgements are due to the scientists for prompt and informative abstracts, to Kathleen Dillard for typing and Maurice Jefferson for reproduction/assembly.

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INTRODUCTION

The Office of Naval Research supports a broadly based oceanography effort. This volume documents the physical oceanographic aspects, which are presented as abstracts submitted by the principal investigators. The purpose of this introduction is to provide a brief program overview, and to relate a few major components to one another.

The physical oceanography program addresses ocean phenomena on scales from ocean basins to turbulence. A division into four general areas is made to distinguish the principal efforts: General Circulation, Mesoscale Variability, Small Scale Variability and Air-Sea Interaction. We emphasize that this separation, while acknowledged by most oceanographers, has no rigid boundaries. In fact, much of the recent excitement comes from the fascinating and complex range of scale interactions present in the ocean.

General circulation or large scale elements in the program focus on the nearly steady state (time scales of years) and large dimensions (greater than a few hundred km.). Topics of interest include the major gyres, recirculation, western and eastern boundary currents, water masses, and recently, thermocline and ventilation processes. Work is largely observational, but components in modeling and theory are well integrated. On the locator map (p. 132) numbers refer to field efforts according to the key, (p. 131). The index on page v lists alphabetically the components of the large scale effort. As a "quick reference" aide, we have included a few key words to characterize the efforts discussed in the abstracts. In parentheses, we show the general scientific topic(s), the technique(s), and, if appropriate the experiment(s) or geographical site(s).

Mesoscale variability addresses oceanic phenomena of time scales of order of weeks to months, and space scales from tens to a few hundred km. These phenomena include eddies and fronts, and Rossby waves. Program emphasis is on the understanding of the causes of the phenomena, their effect on both larger and smaller scales, and their evolution in space and time. Modeling and theoretical efforts here are quite diverse, since the features involve subtle dynamical balances. Observational programs are underway and are planned for the future in the newly funded Accelerated Research Initiative (ARI) Synoptic Ocean Predication. This ARI seeks to obtain real time data for nowcasts and forecasts of the mesoscale eddy fields, particularly in the Gulf Stream region.

The small scale program embraces those phenomena at time scales typically less than 1 day and of limited spatial extent in the horizontal and vertical although perhaps ubiquitous in their distribution (eg. internal waves). In the program, a series of focused at sea experiments have been mounted recently, since observational limitations at these scales are severe. The small scale program is funded by an ARI in Finescale Variability. The recent experiments include a long term upper ocean study (LOTUS) in the western Atlantic, MILDEX, a mixed layer dynamics experiment off California, and AIWEX, an arctic internal wave experiment in the Beaufort Sea. A future experiment, PATCHEX, will examine turbulent processes off California.

Air-Sea Interaction projects focus on the marine planetary boundary layer (MPBL) and the oceanic boundary layer (OBL). Understanding the various physical processes is the central thrust of the program. An Air-Sea Interaction ARI has supported FASINEX, an experiment to determine oceanic frontal effects on air-sea fluxes and other processes. The experiment will end in FY86. A future experiment, OCEAN STORMS, will investigate strong air-sea coupling off the west coast in FY87-88. Wave physics efforts are increasing, as well.

This introduction highlights but a few of the many exciting research topics in the program. The abstracts that follow provide a more balanced view, but as abstracts, merely whet the appetite. We hope this compilation will encourage a closer rapport among the scientists represented here, and in addition, among the members of the community at large.

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Henry D. I. Abarbanel

HYDRODYNAMICS OF STRATIFIED FLUID AND INTERNAL WAVE INTERACTION

The interaction of mesoscale oceanic flows with the ocean's internal wave field is studied here with the goal of understanding the transfer of energy from the mesoscale to internal waves and the observed spectrum of the internal waves. The mesoscale flow is formulated using Lagrangian fluid mechanics to allow the full dynamical structure of the flow to be retained in the quasi-geostrophic approximation appropriate for small Rossby number.

The present work follows on the formulation of the shallow water equations in Lagrangian form and consists of two main thrusts: (1) the numerical solution of the single homogeneous layer or few layer shallow water equations and their Lagrangian quasi-geostrophic approximation for understanding both the mesoscale dynamics itself and the relation between the exact and approximated form of the nonlinear equations. We are investigating the solutions to the equations in one and two dimensions and in Eulerian and Lagrangian form and in exact and quasi-geostrophic form. This is to give us a clear indication of the limitations and virtues of each formal statement of the mesoscale modes. (2) The formulation of the shallow water equations in the presence of continuous stratification to allow the internal wave degrees of freedom to be included in the problem. The numerical and analytic investigation of the coupled mesoscale and internal wave dynamics will then follow. In this part we will also be considering the solution to the mesoscale-internal wave interaction question in its various formal [Eulerian, Lagrangian, exact shallow water, and quasi-geostrophic] statements.

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1 October 1985 - 30 September 1986

Y.C. Agrawal
E.A. Terray

A Dissipation Laser Doppler Velocimeter for Surface
Layer Observations under Waves

This ongoing work seeks to eventually make observations of the near surface turbulent kinetic energy dissipation under a range of forcing conditions. Specifically, our goals are twofold: first to establish the mean vertical profile of the dissipation and second, to investigate its variability at time scales of order the wave and wave-group periods. Towards this end, a special version of the laser Doppler velocimeter is being developed and tested in this first phase of the project.

The instrument being developed and tested is a modification of the forward scatter LDV developed for the HEBBLE SeaDuct. In the modified version, rather than measuring the two components of velocity (u, w), two estimates of one velocity component (u) will be made at two spatial points separated less than a Kolmogorov length scale apart. Determination of the dissipation from the correlation of the accelerations as measured at these two points produces unbiased estimates, which in conventional single point LDV's are severely biased due to 'phase noise' caused by particle statistics. In the first phase of this program, this twin-velocity estimate LDV (TVE-LDV) will be used in laboratory flows where dissipation statistics are known. In subsequent years, the instrument will be used in surface layer field experiments where advection will be measured by an acoustic BASS sensor and other supporting measurements will be obtained from a suite of meteorological and wave-height sensors.

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Kenneth R. Allen

Fundamental Statistical Formulation of the Oceanic
Geostrophic Mode System

We have obtained a canonical Hamiltonian formulation of oceanic fluid motions which includes the Coriolis effect, internal wave modes, and geostrophic modes. This formulation is in precisely the form required for application of the statistical mechanics methods of Prigogine. The purpose of this project is to obtain the master equation, valid in the weak interaction approximation, which describes the statistical evolution of the geostrophic mode system. The master equation will be used to estimate the relaxation times associated with the geostrophic modes.

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Contract Period

1 October 1985 through
30 September 1986

OCEAN MIXING PROCESSES

Frontal structures have distributions and scales given primarily by the strain field of the large-scale flow, the coherent features of which are distinctive signatures clearly observable in satellite infra-red scanner images. We have found that surface and subsurface gradients and structure of the temperature and salinity field depend strongly on position within these large-scale structures. This is a continuing investigation; satellite observations determining the in-situ sampling strategy. Although the California coast was chosen because of operational simplicity, we believe that only a limited number of coherent structures exist in oceans and that a study of the type begun here will be applicable to other areas as well.

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John M. Bane

STRUCTURE AND ENERGETICS OF GULF STREAM FLUCTUATIONS
DOWNSTREAM OF CAPE HATTERAS

In the region northeast of Cape Hatteras, NC, the Gulf Stream path meanders, typically with amplitude increasing downstream. It ranges throughout an envelope that grows to several times the width of the current itself and frequently interacts with rings and eddies. Previous observational and theoretical modeling studies have raised questions regarding the fundamental dynamical and energy balances governing the meandering. During the past funding period we have been collaborating with Dr. D. Randolph Watts (URI) in observational studies of the structure and energetics of Gulf Stream fluctuations. A large data set was obtained from an array of inverted echo sounders and current meter moorings deployed just downstream of Cape Hatteras in a region of rapid meander growth, and from seven AXBT mappings, which were made to document the Gulf Stream's spatial structure there. The goal of this study was to characterize the full x, y, z , and t structure of the fluctuations and to determine the relative importance of baroclinic and barotropic instability processes in supplying energy to them. The 500 and 1000 m mean velocity vectors from the moored array indicate that the anticyclonic flank of the Stream was positioned over the array during most of the year. A deep counter-current flow towards the southwest at about 4 cm/sec was observed over the 4000 m isobath, just seaward of the Stream's position. Although nearly 100 km shoreward (i.e., northwestward) of its mean position early in the year, the Stream shifted seaward and into the array during April, following the coalescence of a cold core ring with the Stream in the vicinity of the array. While the Stream flowed through the array during the next several months, its variability was dominated by Gulf Stream meanders with periods in the 4 to 40 day band. At least one more cold core ring passage through the array was recorded during late September. On two occasions the movement of a mid-depth, anticyclonically rotating warm eddy through the array was observed. Several submesoscale coherent vortices were also observed to move through the array. Deeper fluctuations below the Stream had characteristics of topographic Rossby waves, with rms velocities of about 6-9 cm/sec, generally southwestward propagation, and periods ranging from about a week to nearly 50 days.

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1/86 - 12/87

Douglas B. Boudra

Studies of the Agulhas Current System
and its Role in the Global Ocean Circulation

This project focuses on the physical/dynamical processes associated with the Agulhas Current Retroflexion region off the South African coast. We have been studying this region using a hierarchy of numerical models examining the wind-driven circulation of the South Atlantic-Indian Ocean and comparing our results with observation. For simplicity, we have represented the two-basin system as a zonally oriented rectangle with an appendage extending from the northern wall representing Africa. As a first approximation, Africa's shape was that of a thin rectangle. The basin is forced with steady zonal winds which vary sinusoidally in the north-south direction. Maximum easterlies are along the northern boundary. Africa is 600 km in length and the westerly wind maximum is 400 km south of its southern tip. The 280 km from this maximum to the southern boundary is forced cyclonically. This provides for a free jet/frontal type feature a few hundred km south of the tip of Africa with which the retroflexion can interact, much as does the northern edge of the Antarctic Circumpolar Current.

Within this framework in a one-layer model, retroflexion was found to be dependent on the southward inertia in the separating Agulhas Current and in the way this inertia influences the change in the vorticity balance as the Agulhas leaves the no-slip boundary for the open ocean (W. de Ruijter and D. Boudra, DSR, 1985). Experiments with a 2- and 3-layer quasi-isopycnic coordinate model revealed a similar dependence on the β -effect in the separating current (D. Boudra and W. de Ruijter, DSR, In press, 1986). Also pointed out was the significance of friction in the western boundary layer and the mechanisms by which Agulhas rings form in the model.

In our current work, Africa has the approximate shape of the South Africa/Agulhas Bank combination. Thus, the magnitude of the β -effect in the model Agulhas has a more realistic relationship to that in the actual Agulhas. The retroflexion dynamics are approximately the same as in the rectangular Africa case, but there is more exchange between the two basins. We are currently focusing on understanding the dynamics of retroflexion and ring formation in terms of the vorticity balance and energy conversion. Recent analysis suggests that ring formation in the model is dominated by baroclinic instability. When computational resources become available we plan experiments with more realistic basin and wind forcing scales.

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10/1/85-9/30/86

Kenneth H. Brink

A LONG TERM STUDY OF THE OCEAN'S RESPONSE
TO FLUCTUATING WINDS SOUTH OF BERMUDA

Data are being collected to test the hypothesis that fluctuating winds over the North Atlantic Ocean can generate measurable subinertial frequency current fluctuations throughout the water column. These fluctuations may dominate the background current variability in the ocean in regions away from the influence of intense oceanic currents.

In order to gather sufficient data, two intermediate moorings were deployed at 25.5°N, 70°W and 28°N, 70°W during October 1984. The two moorings are to be recovered in June 1986. Various wind data are being collected for intercomparison and for a basis of studies of coherence with current fluctuations. The two moorings bracket the FASINEX area, and can also be thought of as a long-term component of that program. The wind data are currently being obtained and archived.

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January 1, 1986-December 31, 1987

Melbourne G. Briscoe

LOTUS

The Long Term Upper-Ocean Study was a two-year field effort in the central Sargasso Sea, during 1982-1984. The main objective was the observation, description and understanding of the variability of the internal wave field as a function of time, wind, depth, surrounding eddy field, and other environmental factors. The data were from a total of 10 moorings including 4 surface moorings, 87 current meters at depths from 5 to 4000m, surface wave and meteorological instrumentation, and hydrographic profiles at each visit to the site. The final data were obtained in May 1984 and the final data report was completed in December 1985 (now in press).

The analysis has concentrated on the description of the internal wave field and the characterization of the atmospheric and low-frequency oceanic forcing fields that contribute to the energy balance of the internal waves.

There are several surprising results to date:

(1) the internal wave field (for frequencies higher than tidal and inertial) has a seasonal variability to 1000m, with a late-winter maximum energy that is ten times the late-summer minimum;

(2) the low frequency eddy field is nearly constant in the top 500m of the water column, instead of the expected surface intensification;

(3) the low frequency currents are coherent with the wind stress at the site in a 2-6 day band, a 20-40 day band, and for periods longer than 100 days.

The analysis is continuing, with concentration on the vertical structure of the low frequency current field and its relation to the wind stress, and the detailed correlation between the internal wave energy variations and the forcing functions.

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1 January 1986 - 31 December 1986

Melbourne G. Briscoe
Albert J. Williams, III

RICHARDSON NUMBER FLOAT

The Richardson number is the ratio of density gradient to squared velocity gradient, with appropriate constants, and when large suggests that the fluid is stable to potential overturning forces. Although details vary according to one's theory of mixing in the ocean, when the Richardson number is small it suggests the fluid is unstable and that mixing will occur.

Our objective is to deploy a neutrally buoyant midwater float that carries instrumentation to measure the Richardson number within the parcel of water in which the float is embedded, for a period of 2-3 weeks during the Patch Experiment (PATCHEX) of Dr. Mike Gregg and co-workers, which is planned for 26 September to 26 October 1986 southwest of Seattle.

The float will be a modification of the Benthic Acoustic Stress System (BASS) used in the HEBBLE and other programs as a bottom instrument; our principal modification is to ballast it for neutral buoyancy and to add a modest depth-adjustment capability. There are six 3-dimensional acoustic velocity sensors on it at vertical spacings of 50cm to 5m, and 8 fast response thermistors. Density profiles from the other investigators in PATCHEX will provide the information needed to convert our temperatures to densities.

The work now involves the float construction and the preparation of an acoustic tracking and position-prediction system to let the ship stay near the float for microstructure profiles. We anticipate a 15-20 day record of varying Richardson number that correlates with nearby dissipation measurements and with estimates of the internal wave field variability.

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1 October 1985 - 30 September 1986

Otis B. Brown
Robert H. Evans

SATELLITE REMOTE SENSING OF LARGE SCALE OCEAN TRANSIENTS

The long-range objectives of this project include study of transient behavior of western boundary currents and associated eddy structures, frontal processes, and their response to atmospheric forcing as observed by satellite remote sensing techniques. Attainment of these objectives requires development of quantitative assimilation methods for satellite data on both large and small scales supported by suitable tools which yield timely analysis of calibrated, navigated satellite observations.

Efforts in the past year have focused on obtaining a multi-year time series of high resolution NOAA AVHRR retrievals for the Brazil Current/Falklands (Malvinas) Confluence, development of an accurate AVHRR calibration, and operation of a global retrieval capability using a DOD furnished satellite receiving system. The confluence work, which started in August, 1984, is proceeding well. A cooperative endeavor with A. Gordon and D. Olson utilized near real time satellite data to guide the R/V Thomas Washington to selected mesoscale features for seeding with drifters during the October, 1984 cruise. Analyses of the limited retrieval set presently available finds large, poleward pulses of Brazil Current water offshore of a Malvinas Current frontal region occurring twice in a two-year record. A longer term analysis (five years) of seasonal SST frontal variability is now underway based on historical satellite data. The full multi-year data is being used for analyses of variability on monthly and longer scales.

Recent development and publication of an improved AVHRR calibration methodology is expected to significantly enhance the quality of passive infrared SST estimates. The DOD DOMSAT receiving system for NOAA polar orbiter data is now in operation for East Coast direct broadcast observations. Global operation is expected by late May, 1986.

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Contract Period 10/01/84 - 09/31/86

Harry L. Bryden

GULF STREAM OBSERVATIONS

The first intermediate mooring extending up into the thermocline of the fully-developed, deep-water Gulf Stream was deployed at the mean position of the Gulf Stream from October 1982 to October 1983. Current meter measurements at nominal depths of 400, 700, 1000, 2000 and 4000 meters have been used to show that the instantaneous Gulf Stream penetrates to the bottom in this region. Also, as the Gulf Stream meanders past the mooring, the combined current and temperature measurements are used to profile the horizontal structure of the Gulf Stream including its potential vorticity. Vertical velocities throughout the water column calculated from the turning of the horizontal current about the vertical are highly correlated with upward velocities at the bottom generated by deep flow across the isobaths. Finally, an analysis of the energetics of the observed mean and fluctuating fields suggests that barotropic and baroclinic instabilities are equally important in the Gulf Stream in this region.

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Contract Period: 1 October 1982 - 30 September 1984

Robert R.P. Chase

Telemetry Systems Project

Phase II: Satellite-Linked, Moored Oceanographic Instrument Systems

The Telemetry Systems Project is a cooperative, research and development effort between four separate Laboratories and groups within WHOI. The purpose of the Project is to push forward with developing state-of-the-art, modular telemetering instrument systems capable of supporting a new research methodology in which synoptic data is acquired in real-time to further develop, initialize, and operationally support research with oceanic forecast models. Phase I of this project concentrated on Lagrangian systems resulting in the RELAYS suite of instrument systems while Phase II builds upon these developments, concentrating on Eulerian systems.

Under the second phase of the project, we have explored both the conceptual and systems level designs of a new generation of moored instrument systems. We have examined the scientific requirements for a next generation system and evaluated various technical solutions against a set of baseline scientific requirements. This work resulted in a modular mooring concept with a suite of near-real to real-time data telemetry subsystems. The choice of telemetry subsystems is dependent upon the specific experiment (i.e. open versus ice covered ocean; high versus low eddy kinetic energy region) to be undertaken.

As currently conceived, modular moorings will be cost competitive with conventional moorings, while providing significantly greater flexibility in data acquisition, sampling strategy, preprocessing, and distribution.

We are now working on the detailed design of the modular moorings per se. We expect to complete this design work during FY 86 and will begin constructing the first prototypes early in the next fiscal year. Existing plans call for deployment of these prototypes in a pilot SYNOPS experiment during the spring of 1987.

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10/1/84-3/31/86

Peter Cornillon

GULF STREAM PATH DYNAMICS: A SATELLITE PERSPECTIVE

This study deals with Gulf Stream meandering from Cape Hatteras to 45°W for the period from spring 1979 through December 1986 using satellite-derived sea surface temperature (SST) fields. The study is designed to complement our NSF-funded research currently in progress. It has been conceived as part of ONR's SYNOP initiative with the objectives tailored to address issues identified at the recent SYNOP workshop as being of general importance. The specific problems to be addressed are the following:

- (i) Gulf Stream path dynamics from 60°W to 45°W;
- (ii) large amplitude disturbances of the Gulf Stream and resulting mesoscale features north and south of the Stream; and,
- (iii) effects of inlet conditions, especially transport, on downstream meandering and shingling.

A byproduct of the research will be a time series of Gulf Stream SST fields and one of Gulf Stream path positions. It is anticipated that these time series will be of interest to the SYNOP experimental team as a whole.

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Contract Period: 1/86-12/87

Peter Cornillon
David Evans

SATELLITE OBSERVATIONS OF THE SUBTROPICAL FRONT(S)

This project consists of two parts, one dealing with the satellite support of FASINEX and the second with the pursuit of specific scientific objectives related to the subtropical front. To date the bulk of the work has been toward the support of the deployment of FASINEX moorings in January and the intensive field program in February.

The support of the deployment cruise, Leg 1, was very successful in that the data reduced the ship-time required to map the front, provided an added level of confidence in the data obtained by the ship, and demonstrated the practicality of satellite-derived data in near real time oceanographic research operations. Support continues in the intensive survey of Leg 2. In the meantime, a chronology of the location and evolution of the front under study is being assembled.

We are pursuing four specific scientific objectives as part of this project:

- (a) Where is the Subtropical Front(s) located and how does it move with time?
- (b) What gives rise to the Front?
- (c) What are the small scale (<50 km) characteristics of fronts in the FASINEX study area?
- (d) What forces these small scale perturbations of the fronts?

Significant progress has been made on the first two objectives and we anticipate completing these this calendar year. In preparation for FASINEX a four-year history of fronts in the general study area (23 to 33°N, 73 to 61°W) has been generated. Also numerical predictions of sea surface winds covering the same period have been obtained from Fleet Numerical Oceanography Center. The relationship between the winds and the location of the front is currently being investigated with specific attention given to the predictions of various models of the forcing of the front.

Objectives (c) and (d) will make use of in situ observations collected during Leg 2 by R/V ENDEAVOR and R/V OCEANUS, by the moorings and by observations made in Leg 1 by R/V KNORR. While on Leg 1, we had one week of clear satellite coverage during which a feature very similar in aspect to a Gulf Stream shingle propagated from west to east past the array. Data were also collected in this feature by KNORR. Its existence, its similarity to features in the Gulf Stream and the in situ data collected in and around offer an excellent opportunity to address objectives (c) and (d). We anticipate the sampling of other similar features during the remainder of the intensive sampling program.

As a first step in the analysis of small-scale (~50 km) features, their frequency of occurrence and similarity in characteristics as seen in the satellite data will be investigated. This will be followed by the numerical simulation of the events; initializing the model with the shape of the feature and then comparing the evolution as shown in the model with that observed. The model is quasigeostrophic and uses the method of contour dynamics to determine the evolution of the front. It was designed by L. Pratt for use with the Gulf Stream, but discussions

with L. Pratt indicate that it may be better suited to following the evolution of fronts in the Subtropical Convergence in that the flow is slower, hence closer to being quasigeostrophic and further from topographic constraints of any kind. We are currently running the model for the Gulf Stream.

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Contract Period: 01/1986-12/1987

BRUCE D. CORNUELLE

STUDIES OF THE OPTIMAL USE OF DYNAMICAL MODELS AND
OTHER PRIOR CONSTRAINTS IN THE ANALYSIS OF OCEAN DATA

I am studying methods for combining ocean data with medium- and large-scale ocean models. The data can be of many different types and can be scattered throughout the space-time region of interest. Because the initial and boundary conditions required by traditional mathematics are not available in these cases, the research focusses on approximate solution methods to find a likely ocean realisation which satisfies the model physics and reproduces the measurements to within experimental errors. One approach to this problem is to use an updating method which uses a numerical model to propagate the ocean estimate forward in time and revises the ocean estimate when new data are available. I have completed some simulations of an updating method using an approximate version of the Kalman filter on mesoscale data, and will have a draft ready for submission soon.

The updating method will now be applied to the mixed dataset from the 1981 ocean tomography experiment, which used several instrument types (including acoustic travel times, current measurements, CTD stations, and T-P records) and extended over about 3 months. This dataset should provide a test of the updating on real data, and the update will also serve as a test of the applicability of linear quasi-geostrophic dynamics to that dataset.

I will soon begin work with Dr. G. Vallis (SIO) to examine predictability times in his baroclinic nonlinear quasi-geostrophic spectral model, which is far more sophisticated than the simple linear model used so far. Dr. Vallis has considerable experience with predictability experiments in non-linear flows, and we hope to see what effect data addition has on predictability times. The new model will also allow us to examine the effects of known or unknown forcing and topography on the predictability of the flows.

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Oct. 1985 - Sept. 1987

Charles S. Cox

CARTESIAN DIVER OBSERVATIONS

The cartesian diver is a free vehicle that makes repeated vertical dives from the surface to a depth of a few hundred meters. It records vertical shear in horizontal water velocity by the GEK method and also vertical velocity, salinity, temperature, and conductivity microstructure.

Observations have been analyzed from MILDEX and 4 other locations. Except for one near shore station where the motions were dominated by low mode internal waves, the data show that the mean square shear is always high (that is, Richardson numbers less than unity) and that the vertical wavenumber spectrum of horizontal velocity is variable. During high energy episodes the low wavenumber part of the spectrum increases and the high wavenumber part steepens so that the spectral intensity for the shortest observed waves (vertical wavelength 2-5 m) remains relatively constant, independent of the total kinetic energy. This picture is consistent with the view that the intensity of the shortest waves is constrained by dissipation in occasional turbulent bursts while the longer waves provide an energy cascade to maintain the short waves.

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Dr. B. Cushman-Roisin

MESOSCALE FRONTS IN THE UPPER OCEAN

The evolution of upper-ocean mesoscale fronts (scale of 100 km or so) is studied by analytical and numerical techniques. Included in this category of fronts are the Gulf Stream north wall, coastal fronts and intense isolated vortices. One regime that is given particular attention is that of the so-called frontal geostrophic dynamics, which involves a specific balance of forces that is a primary controlling factor in the evolution of mesoscale fronts. The corresponding equations are relatively simple and make possible the investigation of new problems such as large-amplitude front stability, ring formation and current-ring interaction. The numerical studies are based on a straightforward and powerful application of the point-vortex method to the frontal geostrophic dynamics.

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Eric A. D'Asaro

ARCTIC INTERNAL WAVE MEASUREMENTS USING THE XCP

The Arctic Internal Wave Experiment (AIWEX) made comprehensive measurements of velocity, salinity, and temperature beneath the ice pack of the Beaufort Sea in March and April, 1985. As part of these studies, 136 profiles of velocity were made in an area several tens of miles around the central camp, using expendable velocity profiles carried in a helicopter. These were supplemented by mobile CTD and expendable dissipation probe (XDP) measurements.

Velocity fluctuations due to internal waves were quite weak compared to those in mid-latitudes, corresponding to an energy level 20-50 times less than the canonical Garrett-Munk levels. The strongest velocities were measured inside of intense, circular eddies. These have little or no expression at the underside of the ice, but produce subsurface velocities measured up to 30cm/s. Four such eddies were found ranging from 12-25 km in diameter. One was surveyed repeatedly for 3 weeks with little change in its characteristics. These eddies appeared as counter-rotating pairs, the clockwise rotating eddy above the anti-clockwise rotating eddy. Turbulence levels were very low both inside and outside an eddy. Present analysis of this data is concentrated on describing both the eddies and internal waves and understanding their dynamics and origin.

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1 October 1985 - 30 September 1986

Eric A. D'Asaro

**MEASUREMENT OF UPPER OCEAN RESPONSE
TO NORTH PACIFIC STORMS USING
AIR EXPENDABLE VELOCITY PROFILERS**

Present models of the upper ocean response to strong storms indicate a strong role for horizontal processes in transferring heat and momentum from the upper ocean to deeper layers. Measurements of these processes under the severe conditions expected in storms is difficult using shipboard instrumentation. This project aims to use aircraft-deployed velocity and temperature profilers (AXCP) to survey the velocity field of the upper ocean before, during, and after several strong North Pacific Storms as part of the OCEAN STORMS experiment in the fall and winter of 1987-88. These data will be combined with meteorological and oceanographic measurements by other investigators to test models of upper ocean thermal structure, currents, particularly inertial currents and turbulence.

Present work in preparation for the OCEAN STORMS experiment includes modelling of ocean response to realistic wind fields measured by the Seasat scatterometer and modelling upper ocean turbulence and internal waves. The principal investigator is also serving as coordinator for OCEAN STORMS.

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1 October 1985 - 30 September 1986

Atmospheric Forcing on Ocean-Atmosphere Boundary-Layer Processes

This effort includes model formulation/evaluation and observational studies on the coupling between structures and processes in the adjacent oceanic and atmospheric layers. The formulation/evaluation tasks examine predicted evolutions in the oceanic and atmospheric boundary layers obtained from bulk models. Observations were made of atmospheric structure and forcing during MILDEX-83. Observations are being planned in the Frontal Air-Sea Interaction Experiment (FASINEX) in February and March 1986.

The objective is to characterize local air-sea interaction in terms of the coupled changes and equilibrium states within adjacent oceanic and atmospheric boundary layers. The characterization is based on measurements and computational resources available to a ship and is for predictions of both mixed layers for periods of 24 to 36 hours. The prediction would be for a point and exclude ocean and atmosphere advection effects.

The approach at present is to:

- a. Evaluate a micro-computer based coupled integrated marine atmospheric boundary (MABL) and ocean boundary layer (OBL) model. Evaluations include sensitivity analyses on exchange coefficients in the coupled MABL-OBL model with existing (MILDEX, STREX) and planned (FASINEX) data sets satisfying one dimensional constraints.
- b. Obtain description of coupled MABL features and ocean forcing from shipboard measurements in experiments when (FASINEX) horizontal gradients at surface are important.

The work is being performed in collaboration with OBL modeling efforts by Dr. R. W. Garwood and with participants in the MILDEX and FASINEX experiments.

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Russ E. Davis

LAGRANGIAN CIRCULATION STUDIES

The purpose of this new program is to develop observational and analytic tools to describe ocean circulation with current following floats. During 1985 this involved two tasks.

1.) In cooperation with Webb Research, considerable progress has been made in developing and testing a vertically cycling neutrally buoyant float for observing large scale currents. A prototype Autonomous Lagrangian Circulation Explorer (ALACE) has been successfully exercised. This device cycles between the surface (where it is located by ARGOS) and depths up to 2000m where it is a current follower. Buoyancy is changed by a battery powered motor and hydraulic pump transferring oil between an internal reservoir and an external bladder. At the surface a unique wave-powered pump increases buoyancy further, decreasing the probability of submergence during ARGOS transmission. Engineering development is continuing and we hope to deploy several ALACEs in the Pacific gyre scale tomography experiment.

2.) The utility of Lagrangian observations for describing general circulation scale property transport is being examined. A model, which takes into account the finite time and space scales of eddy motion, has been used to derive a transport equation for property transport. This transport equation is an elaborated advection-diffusion equation with the diffusivity defined in terms of lateral particle motion. Real floats do not accurately follow vertical velocity but analysis shows the resulting errors in the mean lateral motion and particle dispersion inferred from floats are negligible. Simulations of float motion in two-dimensional geophysical turbulence with mean shear and confining boundaries are being used to test the theoretical transport model and to refine the requirements for sampling and float arrays.

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10/1/85 - 9/30/86

Russ E. Davis

UPPER OCEAN DYNAMICS

For several years this program has sought to describe, through observation and analysis, aspects of the dynamics of the upper ocean and their relation to atmospheric forcing.

Over the years the focus has shifted from the one-dimensional processes investigated in the Mixed Layer Experiment (MILE) towards the two-dimensional processes being examined in the Frontal Air-Sea Interaction Experiment (FASINEX) and the three-dimensional wind response to be examined in the 1987 experiment Ocean Storms.

At the same time the program has concerned the evolution of observational tools for such studies and has invested effort in development of the Vector Measuring Current Meter, shipboard acoustic Doppler current profilers and self-contained Doppler profilers.

Recent activity has been in the following areas:

- 1.) Dan Rudnick, a graduate student, has completed a theoretical examination of frontogenesis in mixing layers. This provides a unified framework describing front formation in convergent flows (as subtropical fronts are supposed to be), in divergent flows (as occurs in forming coastal upwelling fronts), and in regions of localized mixing (as tidal fronts). He intends to extend his analysis in conjunction with analysis of FASINEX.
- 2.) We are presently participating in FASINEX with a shipboard acoustic Doppler profiler gathering data which will be integrated with rapid temperature and salinity profiling from an IOS batfish. This should provide an unprecedented synoptic view of frontal regions.
- 3.) A comparison of velocity observations from a self-contained RD Instruments acoustic Doppler current profiler is in the analysis stage. This is preparatory to participation in Ocean Storms where five profilers will be deployed to observe the three-dimensional structure of the ocean response to strong wind forcing.

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10/1/85 - 9/30/86

Roland A. de Szoeke

DYNAMICS OF THE UPPER OCEAN

The major thrust of my research is the upper ocean's response to forcing by momentum and heat transfer to and from the atmosphere. Hence, I intend to participate in the OCEAN STORMS experiment in 1987-88. My contribution to the core field program will consist of the deployment of a mooring carrying a meteorological package, thermistor chains, and possibly current meters. In this I would collaborate directly with Murray Levine and Clayton Paulson (T-chains and current meters), and Dale Pillsbury (technical support), all of O.S.U.

My scientific objectives are the description of budgets for heat, potential energy, and momentum on the time-scales of individual storms, and the discernment of the contribution of advection, horizontal and vertical, to these budgets. Wind stress forces inertial motions, the most energetic contribution to the spectrum of current, with coherence scales on the order of 50 km. This means that, on the larger scale of a storm system, entrainment proceeds at different rates from point to point depending on the phase between pre-existing inertial current and wind, resulting in a grainy distribution of mixed layer depth. The better description and modelling of this horizontal distribution of inertial currents and upper ocean structure is among my research objectives.

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T. M. Dillon
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OSU MICROSTRUCTURE

Our long-term goal is to learn more about the processes by which heat, mass and momentum are transported in the ocean, and about how kinetic energy and temperature variance are dissipated. We have been testing the applicability to oceanic turbulence of theoretical models, and rules derived from turbulence measurements in laboratories and in the atmosphere. Our most recent experimental efforts have been to measure the microstructure of temperature, conductivity, and horizontal shear in the mixed layer off the California coast as part of MILDEX, and in the Arctic Ocean as part of project AIWEX. Analysis of both these data sets is continuing.

A major result of MILDEX was to successfully measure the kinetic energy dissipation rate near the sea surface with WAZP (Wave Zone Profiler), a microstructure profiler carrying microscale temperature and conductivity sensors, and airfoil shear sensors. WAZP descends to a operator-determined depth, releases a ballast weight, then buoyantly ascends. Turbulence measurements are continued until the sensors break the sea surface. During MILDEX, we observed that the kinetic energy dissipation rate is sometimes well-described by boundary layer models, but at other times may be much larger than boundary layer models predict. It may be that the largest dissipation rates are linked to secondary circulations (possibly Langmuir cells) within the mixing layer.

During AIWEX, we measured microstructure while camped on an ice flow in the Beaufort Sea in March and April, 1985. Over 700 profiles were collected. Turbulence in the Beaufort Sea was very weak, with few turbulent overturns observed below the surface layer. An exception to this rule was seen when a sub-surface mesoscale eddy passed through the observation area; then, moderately large dissipations were seen at the depths where the eddy's shear was maximal. Step-like temperature and salinity structures were always observed somewhere in the depth range 300-500 m. The steps are caused by a double-diffusive instability, and the turbulent kinetic energy dissipation rate in the step region was very small. The heat transported by double-diffusive processes may be the major means of heat transport from the Atlantic water mass to the cooler, fresher Arctic water above. We are presently trying to quantify the double-diffusive heat transport and the intermittent, weak turbulent mixing.

Contract Period:
Nov. 1 1985 to Oct. 31 1986,

Russell L. Elsberry
David Adamec

OCEANIC CURRENT SYSTEM RESPONSE TO TOPOGRAPHY

There has been conflicting observational evidence over the effect of the New England Seamount Chain (NESC) on the path of the Gulf Stream. Surface drifter data have indicated an increase in eddy and meander activity in the vicinity of the NESC. However, digitized satellite data of the position of the Gulf Stream front indicates that, on the average, the Gulf Stream does not feel the influence of the seamounts. The scientific objective of this research is to determine the effect of abrupt topography such as the NESC on the mean path of the Gulf Stream. Numerical models are used to simulate the long term average and time varying energy and flow fields associated with the Gulf Stream. Preliminary results indicate that the effects due to seamounts are felt throughout the water column. However, the effects are mostly confined to areas directly above the seamounts. The response is damped downstream of the seamounts, and there are no apparent effects upstream of the seamounts. A second effect of the seamounts is to shorten the period between times when there is a peak in eddy kinetic energy to 30 days vs. the 60 day eddy energy cycle of a flat-bottom ocean.

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1 October 1985 - 30 September 1986

Russell L. Elsberry
Lynn K. Shay

Ocean Response to Atmospheric Forcing

The focus of this research is on the ocean current response to hurricane forcing. One important aspect of this work is to characterize spatial and temporal scales of the forced, near-inertial wave field using observations and numerical simulations. Current meter observations under hurricane Frederic document significant horizontal variations in the response due presumably to the initial current fields along adjacent sides of the DeSoto Canyon. Simulated current fields indicate that the near-inertial response is sensitive to both the magnitude and direction of the initial current field. The vertical structure of the near-inertial response is dominated by larger wavelengths (low baroclinic modes) in the deep ocean. In shallower water (depths < 1 km), there is evidence of a significant barotropic component as well as a baroclinic response. A second aspect of the research addresses thermal structure changes due to shear-generated turbulence or horizontal advective processes. To address this issue, two drifting buoys and 40 Airborne Expendable Current Profilers (AXCP) are to be deployed in the wake of a moving hurricane during the summer of 1986. The data from this experiment as well as observations from previous field experiments in hurricanes Josephine and Norbert will be combined with numerical simulations to resolve the physical processes that modify upper ocean thermal and current structure in response to hurricanes.

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1 October 1985 - 30 September 1986

Charles C. Eriksen

UPPER OCEAN DYNAMICS

The aim of this project is to understand the evolution of mass, momentum, heat, and salt structure in the upper few hundred meters of the ocean. Atmospheric forcing is applied to this upper region of the ocean and the deep ocean is forced in turn by processes of advection, diffusion and wave motions occurring within this region. The particular approach taken in this project is observational and dynamical. Observations of current, temperature, and salinity structure are collected and used to suggest physical models for the processes observed.

Specifically, a moored upper ocean current and density profiling instrument called the PCM (for Profiling Current Meter) has been used to collect time series which describe upper ocean evolution over up to 200 m of depth. Observations made with this instrument over opposite four-month segments of the year give a detailed description of the seasonal cycle of stratification evolution at a site midway between Cape Hatteras and Bermuda in the western North Atlantic (the LOTUS experiment). Although temporal changes at a particular location are most often due to advection by currents, vertical diffusion of heat and salt can be inferred from the measurements and its parametric dependence on the strength of stratification and shear examined empirically. In addition, the observations demonstrate that upper ocean internal gravity wave energy and energy flux are modulated by lower frequency currents.

In an attempt to discover the effects of upper ocean frontal structure on air-sea interaction, an array of 4 PCMs together with 5 surface moorings (set by Dr. R. Weller of Woods Hole Oceanographic Institution) has recently been deployed across a front in the subtropical convergence southwest of Bermuda. These measurements comprise part of the joint oceanographic-meteorological Frontal Air Sea Interaction Experiment (FASINEX) whose intensive field work was completed in early March, 1986. The moored array will be used to understand how the presence of an upper ocean front alters upper ocean response to atmospheric forcing as reflected by changes in momentum, heat and salt structure.

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1 January 1986 - 31 December 1987

DAVID L. EVANS

TRANSPORT MEASUREMENTS OF THE BRAZIL CURRENT

Program Objectives

To address the following questions:

1. What is the southward transport of the South Atlantic Western Boundary Current past the seamounts at 20°S?
2. Is there a barotropic Brazil Current?
3. Does Antarctic Intermediate Water flow northward or southward along the coast of Brazil between 32°S and 20°S?
4. Does the transport increase downstream?
5. How strong is the transport in the recirculation region near 30°S?
6. Is there a seasonal signal in the transport?
7. What is the horizontal character of the Brazil Current between 20°S and 32°S? Is it characterized by meanders and eddies or does it flow smoothly along the 200 m isobath?

Present Status and Progress Over the Past Year

Joint funding with NSF has lead to the installation of seven Pegasus transponder sites between 20°S and 24°S. The transponders were deployed in April 1983 and revisited in October 1983 and October 1984. Work to date has addressed all of the above questions at 20-24°S. Remote sensing work (analysis of LAC and GAC AVHRR data) has begun to address these questions with wider geographic scale.

We have made arrangements with the Brazilian Navy Hydrographic Office (DHN) to use their ships. The first such cruise was in October 1984, the next is scheduled for April. The Brazilian space agency, INPE, is collecting two passes per day of AVHRR data and sending them to URI. We have provided large capacity disk storage capability to their data acquisition computer in order to accomplish this.

The plan of the original proposal is delayed by about 3 months due to ship scheduling problems. Pegasus transponders will be deployed between 30-32°S next month. Preliminary hydrographic survey data has been obtained from DHN to aid in locating the transponder line.

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David M. Farmer

ACOUSTIC SCINTILLATION STUDIES

Turbulent tidal flows are being investigated through the scintillation structure of forward scattered sound waves. Flow speed may be derived from the observed translation of the acoustic pattern, while the variability of the signal is related to the temperature and velocity fine structure (D. Farmer and S. Clifford, Oc. Eng., 1986). While various extensions of the basic concept are being explored, including spatial aperture filtering to allow focussing on different parts of the acoustic path, the project is directed towards the study of turbulence and the breakdown of stratification in tidally forced shear flows. Analysis of acoustic phase structure function leads to a measurement of the outer scale of the turbulence. Initial experiments have shown how this scale is a sensitive function of the flow speed and stratification.

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Contract Period:
1 May, 1985 - 30 April, 1986

(Shared with: Upper Ocean
Boundary Layer Studies
from USS DOLPHIN)

David M. Farmer

UPPER OCEAN BOUNDARY LAYER STUDIES FROM USS DOLPHIN

Studies of processes in the upper ocean boundary layer are being carried out from the USS DOLPHIN, using high frequency acoustic backscatter. In addition to scattering from the sea surface, the clouds of bubbles formed by breaking waves are detected. Bubble concentrations over a range of sizes may be inferred from the target strength as a function of acoustic frequency. The bubble population, cloud shapes and spatial distribution, together with related measurements including temperature and velocity microstructure, provide the basis for testing models of organised structures and turbulent diffusion in the upper ocean boundary layer, and the mechanisms for gas flux across the air-sea interface.

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Contract Period:
1 May, 1985 - 30 April, 1986

(Shared with: Acoustic
Scintillation Studies)

David M. Farmer

AMBIENT SOUND STUDIES OF AIR-SEA INTERACTION PROCESSES

A study of the acoustic signature of air-sea interaction processes is being carried out using a combination of ambient sound and active sonar schemes. The relationship between wind stress and ambient sound detected beneath the surface is explored with drifting and moored sensors in both vertical and horizontal arrays. The dependence of temporal and spatial variability and spectral properties are interpreted with the aid of a theoretical model of the wave-breaking process and the effects of bubble clouds. The distinct properties of sound generated by rainfall are investigated. A deployment in the FASINEX study allows comparison with direct observation of wind-stress through a range of stability conditions. Simultaneous measurement of bubble population distribution by multifrequency echo-sounding provides a basis for testing models of the influence of bubbles on the observed levels of ambient sound.

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Contract Period:
30 June, 1985-31 October, 1985

Rana A. Fine

WATER MASS MODIFICATION IN THE AGULHAS
RETROFLECTION REGION USING FREON DATA

Analysis of freon and hydrographic data from the Fall 1983 Agulhas Retroflection cruise shows the importance of the region in modifying the thermocline and Intermediate waters of the South Indian Ocean. The retroflection region is a crossroads for the mixing of water masses from three geographical areas: South Atlantic, South Indian, and sub-Antarctic sector (Gordon, A., EOS, 1986). Strong interleaving regions are found throughout the survey area between 15 and 4°C. These are characterized by correlations of negative salinity anomalies with high freon concentrations; they are used to calculate a diffusive time scale for the mixing of about 10 years. The active mixing in the region may be the reason that the South Atlantic and Indian thermoclines are coincident between 15 and 7°C in temperature and salinity space (Gordon, A., SCIENCE, 1985). The percentage of modern ventilation calculated using freon data are measurably different for the South Atlantic and Indian. Between 15 and 4°C South Indian waters have a lower percentage of modern ventilation giving them an apparent age that is 5 years younger than the South Atlantic waters. South Atlantic waters are closer to the convective source regions, i.e., the sub-Antarctic sector of the South Atlantic. Whereas, the Agulhas serves as a ventilation window for the South Indian thermocline. The waters leaving the retroflection have been modified relative to those entering as follows: upper waters (18°C) by mixing with Subtropical Mode Water formed in the retroflection region; in the temperature range 14 to 13°C by mixing with South Atlantic water; from 12 to 4°C by mixing with water from the sub-Antarctic zone.

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October 1, 1984-September 30, 1986

N.P. Fofonoff

The long-range objective of this research is to incorporate satellite measurements routinely into planning and execution of future array experiments. More immediate objectives are to develop techniques to compare measurements from previous experiments starting with current meter, float and IR data in 1983. Specifically, I have been working on programs to compare satellite IR data with direct measurements by current meters and floats in the Gulf Stream region. A number of computer programs were written last year to subsample and remap the satellite images and to overlay them with coastlines, bottom contours and velocity vectors from in situ measurements.

A joint project (funded by NSF) with Peter Cornillon of URI is in progress to digitize the Gulf Stream thermal front positions between Cape Hatteras and 58°W. These data provide an irregular series of spatial configurations of the Gulf Stream for a 7-month period (Mar.-Oct., 1983) during deployment of H. Bryden's Gusto Mooring and N. Hogg's Abyssal Circulation Experiment. In addition, about a dozen SOFAR floats were released in the Sargasso during this period.

The preliminary comparison revealed several novel aspects of Gulf Stream behavior. During the 7-month comparison period, several ring formation events occurred. The float data showed evidence of much stronger interaction with the Sargasso than expected. In one case, a 700-m float moved northwest from near Bermuda into a Gulf Stream meander at speed reaching 40 cm/s, traversing the entire recirculation gyre. In another case, a meander that did not propagate downstream developed upstream of the New England seamounts. Both upstream and downstream portions of the Gulf Stream remained stationary as the meander grew in amplitude. After about 6 weeks, meanders developed rapidly along the entire front and the stationary meander began to migrate downstream. The comparisons of IR images with in situ measurements and model data will provide new interpretations of Gulf Stream behavior and insight into the governing dynamics.

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ONR Annual Report

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Aircraft Measurements in FASINEX

In the contract period, work proceeded on the development and installation of equipment for turbulence, meteorological and oceanographic (sea surface temperature) measurements on the NRL RP-3A (Buno 149670) aircraft for the FASINEX experiment to be conducted between February 10 and March 15, 1986.

A. As of 1 January 1986, all of the equipment has been installed, which consists of:

1. Radome Wind and Turbulence System

- a. 5 holes in existing radome
- b. 3 pressure transducers

2. Static and Dynamic Pressure

- a. 1 static pressure transducer installed off of research static pressure ports.
- b. 1 differential pressure transducer installed off of co-pilot's Pitot-static tube.
- c. 1 absolute pressure transducer installed off of co-pilot's Pitot tube.

3. Inertial Navigation

1 Litton LTN-51 inertial navigation system (borrowed from the National Center for Atmospheric Research) installed and wired to data system.

4. Data System

1 ARIS IV data system (borrowed from the National Center for Atmospheric Research) installed. Large capacity tape drive rented.

5. Temperature

- a. 1 Rosemount air total temperature sensor (borrowed from the National Center for Atmospheric Research) installed.
- b. General Eastern dew point temperature system (obtained surplus from USN China Lake and sensor purchased by Code 7784, NRL) installed.

c. 2 Barnes 14-325 infrared meteorological radiometers (obtained surplus from USN China Lake) installed: 1 downward for sea surface temperature, 1 upward for monitoring infrared cloud temperature.

6. Altitude

1 APN 232 high altitude radar altimeter (borrowed from NAVAIR REWORK, North Island) installed and interfaced to data system.

B. A tower fly-by was conducted with the P3 past the NOAA Boulder Atmospheric Observatory 330M (1000 foot) tower near Boulder, Colorado on December 12, 1985 in order to determine the static pressure defect as a function of airspeed for the special research static pressure ports on this particular P3. The tests went well, and showed negligible airspeed dependence.

C. An infrared sea surface temperature system using one of the Barnes 14-325 units was assembled for use in FASINEX on the R/V Knorr.

D. A FASINEX aircraft planning meeting was held at the Research Aviation Facility of the National Center (NCAR) for Atmospheric Research in Boulder, CO on December 13, 1985 to plan for the operational aspects of the six FASINEX research aircraft. With the aid of the Flight Support Detachment at NRL, a safe "rendevous" procedure was developed and passed to all flight crews.

E. Notification was received of the participation of the NCAR election in FASINEX, but with flight hours reduced from the requested 80 hours to 50 due to a NCAR problem in obtaining sufficient temporary flight crew for back-to-back flights.

Roland W. Garwood, Jr.
Patrick C. Gallacher

STUDIES OF THE OCEANIC PLANETARY BOUNDARY LAYER

The interaction of planetary rotation with Reynolds stress was studied for a steady-state mixed layer with no entrainment. The results demonstrated that the fundamental properties of the rotation-stress interaction would provide a limit to deepening at midlatitudes (Garwood et al., JPO, 1985). Furthermore, the limiting depth of mixing predicted by the model for the tropical Pacific compared favorably with observations, explaining the very deep mixed layer in much of the tropical Pacific (Garwood et al., JPO, 1985; TO-AN, 1985).

Our studies of the interaction of planetary rotation with Reynolds stress have been extended to the general case, which includes active entrainment, at midlatitudes with the beginning of a series of simulations at OS Papa (50N, 145W). Preliminary results demonstrate the potential for rotation-stress to replace the ad hoc dissipation enhancement required in earlier mixed layer models to limit the late winter deepening of temperate mixed layers and to improve the comparison between the model and the observations (Gallacher and Garwood, EOS, 1986).

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October 1, 1985 - September 30, 1986

Silvia L. Garzoli

BRAZIL/MALVINAS CONFLUENCE: TIME-SPACE VARIATIONS OF THE FRONT

During November, 1984, a small array of inverted echo sounders have been deployed in the southwestern Atlantic at the confluence of the currents from Brazil and Malvinas and recovered in June, 1985 as a pilot experiment for a larger array of sounders in the area to monitor the geostrophic transport of the Brazil Current and to study the time and space variations of the strong thermohaline front originated at the confluence.

The temporal variation on dynamic height due to local dynamics (i.e. the presence and duration of a cold intrusion, the migration of the currents) are inferred from the recorded data. From the dynamic height series, the geostrophic velocities are calculated, the fluctuations of the current between stations analyzed and an estimated value of the transport obtained. This last one, ($17 \times 10^6 \text{ m}^3/\text{sec}$) is in good agreement with the previously calculated from hydrography.

The front oscillates around its mean position with a period of about one month and mean amplitudes that vary from 10 to 50 km. The velocity of displacement reaches values up to 10 km/day. An estimate of the wind speed at the surface is obtained from the ambient noise detectors with an error of 1.8 m/sec. Interesting differences, at low and high frequencies, appears between the winds at both locations only 180 km apart.

The simultaneous analysis of ocean and atmospheric records, provides information on the wave dynamics of the area. The on-shore deployed sounder detected an atmospherically forced oscillation that can be interpreted as a Kelvin wave that propagates along the coast with a wavelength of 5000 km and a period of 21 days. At the off-shore location, the dominant feature in the synoptic scale band is an oscillation, forced by the atmosphere at a period centered on 31 days that might have its source of energy in the tropics.

During the 1985 cruise, three instruments have been deployed at the original locations to maintain the sites for a total of 16 months to determine the seasonal signature of the phenomena described above.

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5/1/84 - 9/30/86

Catherine Gautier

ATMOSPHERE-OCEAN HEAT EXCHANGES FROM COMBINATIONS
OF SATELLITE MEASUREMENTS

Our research, during the first year, has mostly been aimed at analyzing the net surface radiation radiation flux, during MILDEX and preparing for the FASINEX project. We had three specific objectives. First to validate and assess the accuracy of the satellite methods we have developed to compute the shortwave and longwave radiation by comparing our estimates with the surface radiation measurements made during MILDEX. Second, to compute the net radiative flux (shortwave and longwave) field at the surface, during MILDEX and thirdly, to analyze the resulting fields in the relation with the other meteorological and oceanographic measurements. We have found that the accuracy of the shortwave component is about 12 w/m², that of the longwave is about 20 w/m² (Gautier and Frouin, 1986a, Proceedings of ESA Conf.) and that the overall accuracy of the net radiation estimates is about 30 w/m², on a daily basis. The first fields that we have computed (Gautier and Frouin, 1986b, Proceedings of Radiation Conf.) appear very reasonable and show the strong modulation of the radiation by clouds and the significant role played by the longwave flux on the net flux. We are now ready to process the data that will be collected during FASINEX.

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A.E. Gill

Ocean Modelling Newsletter

The newsletter continues to attract more readers and contributors world-wide. The mailing list now exceeds 700, and 1985 saw the publication of 5 issues containing 22 articles, plus sundry announcements. Issue number 66 was printed in January 1986, and issues 67 and 68 are in preparation. During 1985 production of the newsletter was transferred to Oxford following the move of all personnel involved from Cambridge to Oxford, and a new contract with Oxford University commenced. The newsletter is still printed in Cambridge, where substantially cheaper rates are available along with a mailing service.

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June 1985 to May 31 1988

Arnold L. Gordon

SOUTH ATLANTIC OCEANOGRAPHY

The South Atlantic subtropical gyre is unique in a number of important aspects. At its southeastern "corner" the vigorous circulation of the Agulhas Current (70 sv transport relative to 1500 m), the western boundary current of the South Indian Ocean, impinges directly into the more tranquil eastern boundary upwelling regime of the South Atlantic. Energetic eddies drift into the South Atlantic from the Agulhas Retroflexion and a branch of the Agulhas Current, at times, directs warm South Indian Ocean thermocline water (with inclusion of tropical Indian Ocean water), into the Benguela Current system. Within the Agulhas retroflexion itself there is intense water mass modification: the warm thermocline releases great amounts of heat into the cold atmosphere forming deep isothermal winter mixed layers, with relatively high salinity; and South Atlantic "transitional" water masses are swept into the retroflexion along the eastern edges of the Agulhas warm core rings, mixing with Indian Ocean water. Within the southwestern "corner" the Brazil Current, an anomalously weak western boundary current, attains its strongest expression (about 20 sv within the upper 1500 m; 10 sv is characteristic further north, suggesting the existence of a recirculation cell in the SW Atlantic), before encountering the Malvinas (Falkland) Current. Both currents turn seaward in a Rossby Wave pattern with many associated fronts and numerous warm and cold core eddies. The interaction of the Agulhas with the South Atlantic, which introduces heat into the Atlantic thermocline, coupled with the weak Brazil Current, may be responsible for the northward directed heat flux across 30° S in the Atlantic. It is likely this situation is associated with a global scale thermohaline circulation cell associated with North Atlantic Deep Water.

Study of these aspects of the South Atlantic are pursued with arrays of CTD hydrographic and tracer data, satellite tracked drifters and IR images: KNORR data set from late 1983 in the Agulhas Retroflexion region and WASHINGTON data set from October 1984 in the Brazil-Malvinas confluence region.

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10/01/85 - 09/30/86

Michael C. Gregg
Wayne Nodland

UPPER OCEAN MIXING PROCESSES

The principal objectives are (1) to define the major mechanisms producing mixing and to parameterize the dissipation rates and diapycnal fluxes (across density surfaces) in terms of variables that can be measured routinely; (2) to integrate realistic estimates of mixing into studies of large-scale processes; and (3) to synthesize information about mixing obtained from numerical simulations of large-scale processes, from theoretical and observational studies of internal waves, from laboratory experiments of shear instabilities and stratified turbulence, and from oceanic observations of fine and microstructure.

Defining the mechanisms producing mixing and parameterizing their intensity requires intensive measurements of the centimeter-scale fluctuations and of the larger-scale finestructure in which they are imbedded. The microstructure measurements are made with the Advanced Microstructure Profiler (AMP), a free-fall instrument that is loosely tethered to the ship by a 2-mm-diameter Kevlar line containing a fiber optic data link. The AMP carries sensors for velocity and temperature microstructure, as well as for temperature, electrical conductivity, and pressure. The finescale shear field is measured with ship-board Doppler acoustic profilers, with Expendable Current Profilers (XCPs), and with the free-fall Multi-Scale Profiler (MSP). The full three-dimensional environment is determined with CTD tow-yos or by working with investigators using towed thermistor chains or depth-cycling towed bodies on other ships.

The local measurements are imbedded into studies of large-scale processes by sampling in the major oceanic regimes, often as part of co-operative experiments with many investigators doing long-term moorings, synoptic surveys, and satellite imaging. Recent programs have been conducted to study mixing in the upper thermocline (Gregg et al., *JPO*, in press), free convection during cold air outbreaks in the North Atlantic (Shay and Gregg, *Nature*, **310**, 282-285, 1984), turbulence in the equatorial undercurrent (Gregg et al. *Nature*, **318**, 140-144), and hydraulics and mixing in the Strait of Gibraltar.

The major aspects of diapycnal mixing in the thermocline were synthesized in a review paper prepared for a recent international symposium and submitted to *JGR* for the special issue of papers from the meeting. A more extensive synthesis is being done to produce a monograph about oceanic mixing in collaboration with Chris Garrett.

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Michael C. Gregg
Thomas B. Sanford

SHEAR AND MIXING: AN EXPERIMENTAL APPROACH

Most mixing in the thermocline is believed to occur when internal wave shear produces local overturning. The principal objective of this project is to define how this occurs by making measurements of microstructure, shear, and density from the same instrument. The Multi-Scale Profiler (MSP), developed to meet these objectives, carries microstructure sensors for velocity, temperature, and electrical conductivity and finestructure sensors for shear, temperature, and electrical conductivity. With these the full velocity and density fluctuations over scales of 1 km to a few centimeters can be profiled. Making all of the relevant measurements on one instrument has proven necessary because the scale of most mixing events is smaller than the depth uncertainty when measurements made from separate instruments are compared.

The MSP has been tested at sea and is now fully functional. It was used in November 1986 in the NSF-funded C-SALT experiment to examine the extensive salt fingering field east of Barbados. These measurements produced a major surprise because the viscous dissipation rates were much smaller than expected, forcing a re-examination of the application of laboratory double diffusion experiments to the ocean. The prominent layers that identify the salt fingering field were found to be relatively well mixed in momentum as well as in heat and salt; most of the shear was concentrated across the interfaces.

The MSP will be a major component of the ONR-funded Patches Experiment (PATCHEX), which will examine the evolution of mixing rates in a tagged parcel of water, as well as working in the acoustic beams from FLIP. PATCHEX is scheduled for October 1986 in the eastern North Pacific as a cooperative experiment with G. Rudd's group at the Naval Research Laboratory, with M. Briscoe and A. Williams III at Woods Hole Oceanographic Institution, and R. Pinkel at the Scripps Institution of Oceanography.

Future work is planned in the Gulf Stream and in the equatorial undercurrent, also as cooperative efforts.

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1 October 1985 - 30 September 1987

Robert L. Haney

EDDY GENERATION MECHANISMS IN
EASTERN BOUNDARY CURRENT REGIONS

This project is to investigate processes responsible for the generation, evolution and decay of intense synoptic scale variability observed in eastern boundary current regimes, with particular application to the California Current region. It's ultimate goal is to enhance our understanding of eddy generating processes in such regimes, and to thereby provide a basis for high resolution numerical analysis and prediction in these ocean regions.

A 10-level primitive equation ocean model with surface layer physics has been adapted to include an idealized Mendocino Escarpment and continental slope along a straight meridional coastline. The model is in sigma coordinates (non-dimensional depth) and has open boundaries (radiation condition) on all but the eastern coastal boundary. We are presently studying the response of idealized flows over the escarpment for which there are analytic solutions. Model sensitivity studies will be made to determine the dependence of the solutions on the parameterization of sub-grid scale processes and on the choice of boundary conditions on the flow at the bottom, on the slope and at the eastern boundary. We expect to study the eddy generation process in response to seasonal and "event" type wind relaxations as well as a number of different mean flow regimes which have been observed upstream of the Mendocino Escarpment. The ultimate goal is to understand and predict the generation of synoptic scale eddies which are being observed south of Cape Menodcino by the OPTOMA program.

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Contract period: FY86 and 87

Frank S. Henyey

INTERNAL-WAVE NONLINEAR INTERACTIONS BY THE EIKONAL METHOD

We have been exercising a model for the transport of small-scale internal waves. This model is based on ray tracing, and calculations are done by Monte-Carlo methods, since transport theory methods are inadequate for many aspects of the problem.

We used the model to predict the energy dissipation rate, ϵ . We formulated a simple analytic model which, although its a priori justification is weak, agrees fairly well with all features of our calculated dissipation. Using exponential stratification and Garrett-Munk forcing waves, the analytic model predicts $\epsilon = 6.4 \times 10^{-11} \text{ W kg}^{-1} [N/N_0]^{-1} \cosh^{-1}(N/f)$, and our numerical results approximately follow this curve.

We are using the model to predict some characteristics of patches of microstructure which result from internal wave "breaking". We have found that our model predicts that these patches form at places where the shear values of the larger scale flows are large, so that the small wave breaking is catalyzed by larger waves. We are in the process of determining the model's predictions for the patch geometry.

We are, in collaboration with C. Cox of SIO, putting our code on the Cray supercomputer, where we will replace the exponential stratification and Garrett-Munk forcing waves with parameterizations of actual conditions which have occurred in Cox's experiments, so we can make calculations which can be compared to data in a meaningful way.

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Nelson G. Hogg

ABYSSAL CIRCULATION OF THE WESTERN NORTH ATLANTIC
and
A COHERENT ARRAY FOR HEBBLE

We are now in our fourth and final year of a program aimed at gaining a new understanding of the Gulf Stream Recirculation: What does it look like? and How does it work? The project has involved both a field program (current meter moorings and hydrographic work), data analysis, simple theory and some numerical modeling. We have identified a new recirculation gyre to the north of the Gulf Stream and have been able to define its geographical limits and transport. A simple theory suggests that it is nearly potential-vorticity conserving. Assuming also that the potential vorticity is homogenized, one can calculate the strength and size of the gyre, quantities that agree well with the observations. Tracer properties also are homogeneous within the gyre (in the deep water) to within measurement error.

A simple advective-diffusive numerical model has been used to study the manner in which tracers can be diffused into the recirculation gyre from the Deep Western Boundary Current.

Our attention is now turning to the dynamics of the low frequency motion field, as revealed by the current meters. We are investigating such problems as radiation from the Gulf Stream and its relation to the topographic wave field found on the Continental Rise, and the distribution of eddy flux quantities as an indication of eddy-mean flow interactions.

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January 1, 1986 - December 31, 1986
October 1, 1984 - March 31, 1986

William R. Holland
James C. Evans

NUMERICAL STUDIES OF THE GULF STREAM SYSTEM

Substantial progress has been made toward developing a hierarchy of models suitable for prediction and dynamical understanding of the SYNOP region. A limited area, multilevel, quasigeostrophic (QG) model has been formulated, including open boundary conditions, and a sequence of calculations is underway to examine both dynamical and modeling issues. Calculations have already shown the important roles of both bottom topography (the New England Seamounts and other bottom features) and the eastern boundary conditions. This work is quite computer intensive and large resources in computer time and manpower are necessary, given the very high resolution nature of this work.

A second model with active thermodynamics, using the primitive equations (PE), is under development. Much that is learned in the QG model studies above about how to handle open boundary conditions can be transferred to the more realistic PE model. This model will be more suitable for initialization with real data (satellite sea surface temperature and topography) and for data insertion in a predictive mode. Our intention is to carry out very high resolution studies for the region bounded by the North American continent on the west and north, by 25°N on the south, and by 40°W on the eastern side of the domain.

Analysis techniques of local energy and vorticity balances are being developed to understand the dynamical process occurring in these models. Various kinds of initialization and data insertion techniques are being studied and various methods of treatment of open boundaries of a limited domain are being examined.

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1 March 1986-28 February 1987

William R. Holland
Dale B. Haidvogel

NUMERICAL STUDIES OF THE SOUTH ATLANTIC
AND SOUTH INDIAN OCEANS: BOUNDARY
CURRENTS AND WATER MASS PROPERTIES

A two prong modeling effort is continuing beyond the initial development of models of the South Atlantic region. The long-term scientific goals of these modeling efforts include: (1) an assessment of the distribution, generating mechanisms, and role of mesoscale eddies and an examination of the novel features of the western boundary currents (Agulhas and Brazil Currents); and (2) a study of water mass formation/conversion processes in this region.

Rapid progress has been made on these projects. Eddy-resolving models of the Agulhas and Brazil/Falklands regions have been constructed and numerical studies are underway to understand the origin of mesoscale eddy features in these regions. The important eddy/mean flow interactions are the primary focus of this work.

For the water mass formation problem, we have developed and tested a coarse resolution primitive equation (PE) model of the South Atlantic Ocean, including adjacent regions of the South Indian Ocean and Circumpolar Current. Model spin up at this resolution has been completed and the horizontal resolution of the model refined to a two degree grid spacing. A variety of numerical experiments are underway to examine the penetration of influence into the ocean interior after an abrupt change in forcing. Passive tracer intrusions will be a key diagnostic in understanding the basin scale processes.

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1 February 1985-31 December 1985

Greg Holloway

DYNAMICS OF SMALL SCALE VARIABILITY

Disequilibrium, strong interaction statistical dynamics theory is tested for quantitative skill by comparison with direct numerical simulation of internal wave breaking and turbulence. Earth's rotation is included and different flow regimes as characterized by turbulent Froude number are examined. Distributions of kinetic and potential energies in wavenumber and frequency are obtained. Energy transfers and the cospectrum of vertical buoyancy flux are obtained. Numerical experimentation is further pursued to examine the relation of occurrences of sites of intense dissipation with respect to large scale flow features. Field and laboratory comparisons are made.

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86/04/01 - 87/03/31

T. M. Joyce

KUROSHIO EXTENSION AND NORTH PACIFIC CTD STUDIES

Two pairs of deep CTD/O₂ sections were made at 165°E and 175°W in 1983 and 1984 between nominal latitudes of 28°N and 43°N across the Kuroshio Extension. Data have been processed for all sections and a manuscript prepared for the 1983 data. We are currently modifying the paper to include results from 1984 as well. While some differences in the hydrographic characteristics in the two occupations were observed (wider Kuroshio & Oyashio jets at 165°E in the second year), the overall character is quite similar. Total baroclinic transport in the Kuroshio jet at 165°E is 54 ± 2 Su. At 175°W the jet-like flow of the Kuroshio and Oyashio at 165°E is no longer present. Baroclinic transport at 175°W is dominated by eddies with scales of 150-200 km.

Abyssal water mass characteristics were investigated using these data together with other recent CTD stations in the sub-Arctic Pacific Ocean. Large-scale changes in the near-bottom potential temperatures, but not salinities, were observed in the deepest kilometer of water in the region. Variations of .05°C were observed at 47°N with the warmest water in the northeast. Meridional variations of .04°C displayed more structure with lowest temperatures in the sub-tropical gyre and to the south of the Aleutians with an intermediate maximum. These large-scale variations are consistent with geothermal heating through the abyssal sediments. A bottom heat flux of 50mW/m² is capable of changing the potential temperature in a kilometer-thick layer .04°C/100 years. Thus potential temperature is a non-conservative indication of geothermal heating in the abyssal North Pacific.

Larger heat fluxes from more active geothermal regions can alter the deep flow and create westward-tending β -plumes. Earlier work of Stommel has been extended to allow for β -plumes in the presence of a background abyssal circulation. An important ratio for the solution is that of the background eastward current and the phase speed of long baroclinic Rossby waves. Because vertical modes have different phase speeds, the background circulation can cause significant modal dispersion of the β -plume.

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Contract Period: 1 Oct 1984 - 30 Sept 1987

Timothy W. Kao

Gulf Stream Front Modelling

The Gulf Stream current structure is associated with the quasi-permanent density front in the Western North Atlantic. The lighter mass of warmer but saltier water of the Sargasso Sea is separated from the slope water by inclined isopycnals which form the front. Recent satellite altimeter measurements have also revealed a well-defined sea-surface height change across the front. In this work, a model of the Gulf Stream cross-sectional density and current structures is constructed, using the complete dynamical and mass-conservation equations. The model postulates a forcing by an ageostrophic inflow of light water from the Sargasso Sea in the upper ocean and a return flow at greater depths. The Gulf Stream is found to develop after initial geostrophic adjustment of several inertial periods.

The results are compared with representative field data from (i) the Gulf Stream '60 experiment, (ii) the SEASAT altimeter experiment, and (iii) the recent Gulf Stream current measurements by the University of Rhode Island group using the Pegasus current profiler. Quantitative agreement between the model results and the field data is found. The use of the model as a diagnostic tool in conjunction with remote sensing is indicated.

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Aug. 1, 1985 - July 31, 1986

Kristina B. Katsaros

FASINEX EQUIPMENT

In the Frontal Air Sea Interaction Experiment taking place in February 1986 off Bermuda one of the goals is to measure effects of a sea surface temperature front on the atmospheric boundary layer structure. Our contribution to this goal is to measure shortwave and longwave irradiances on two ships stationed on either side of the front. Since we needed two complete stations and would not be able to participate in the cruises due to limited space, we had to prepare two radiation stations with self-contained recording units. We also wished to test a result of J. E. DeVault and K. B. Katsaros (J. Atmos. Sci., 1983) that the ratio of the transmittance in two broad solar bands (blue-green and near infrared) depends on the liquid water content of the cloud. For this purpose we acquired two pyranometers with RG 695 Schott filters and two programmable data loggers with cassette recorders. Time series of the net radiative heat budget at the sea surface will be produced for the two stations from the irradiance measurements and by calculating shortwave and longwave exitances using albedo (after Payne, J. Atmos. Sci., 1979) and the Stefan-Boltzmann formula, respectively. The equipment was acquired and installed on the R/V Oceanus and R/V Endeavor during the first weeks of February 1986.

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5/1/85-9/30/87

Thomas Keffer

STUDIES ON THE CIRCULATION OF THE
NORTH PACIFIC SUBTROPICAL GYRE

This program looks at the mean and time-dependent motions and temperature variability of the eastern subtropical North Pacific, using data from two moorings deployed in July, 1982, along 152°W. This is a two year program, now at the start of its second year. The intention is to gain an understanding of what causes the temperature and velocity variability in this section of the world ocean. This area is particularly interesting because of its remoteness from the eddy generating regions along the western boundaries (in this case, the Kuroshio). In the absence of this eddy "noise", clear signals from wavelike features (barotropic and baroclinic Rossby waves) can be extracted, making the results generalizable to the rest of the world ocean.

Three years of data will be collected. Two are now in hand and the third by late winter. We are now in the process of analyzing the time-dependent temperature and vorticity balances. The first year of data shows a pronounced cooling throughout the thermocline during mid-winter. It is important to note that this cooling is not the result of direct atmospheric forcing that can be expected at shallower (<200 m) depths. Rather, it is a seasonal event and the result of two effects: (1) a rising of the thermocline due to the onset of Ekman suction during winter (Ekman pumping prevails during the rest of the year) and (2) a southward movement of the water column, advecting in cooler water from the north. In short, this area became more "subpolar" during the winter of 82-83.

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Contract Period:
October 1, 1984 - September 30, 1986

A. D. Kirwan

Identification of Causes and Effects of Mesoscale Variability

The long-term goal of this research is to identify the mechanisms by which mesoscale ocean motions transfer energy between larger and smaller scales. Recent emphasis is on deducing mesoscale kinematic characteristics from Lagrangian data from several data sets utilizing a parametric model developed by Kirwan (Tellus, 36A(2), 211-215, 1984) and tested by Kirwan et al. (JGR, 89(C3), 3425-3438, 1984). This model decomposes the drifter velocities into large and mesoscale components. Then through an inversion technique mesoscale spatial kinematic characteristics are inferred. For example, for a drifter trapped in an eddy the analysis provides a time series of the movement of the eddy center while also accounting for distortion of the eddy and any horizontal divergence, if present.

The model has been applied to drifter data from the North Pacific. The mesoscale characteristics as inferred from the drifter data are being compared with concurrent hydrographic data. Preliminary results indicate that Rossby waves of period of the order of one month regularly propagate across the eastern Pacific.

As part of the Southern Oceans Studies Special Focus Program, analysis of mesoscale and large scale variability is being conducted in collaboration with the University of Miami group. A detailed comparison is being made between drifter data, satellite imagery and XBT data for several South Atlantic eddies off the Capetown. A consistent picture of the vorticity and horizontal velocity shears within these structures is emerging from these studies.

Recently we have compared the kinematics of two large anticyclonic rings in the Gulf of Mexico with simulated drifter data from the Hurlburt-Thompson general circulation model. Kinematic characteristics of the simulated data are remarkably similar to that calculated from the observations.

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1 May 1986 - 30 Sept. 1988

John M. Klinck

MODELLING OF THE CIRCULATION IN A CANYON/SHELF SYSTEM

The objective of this study is to understand how a geostrophic current interacts with a narrow, transverse canyon. The starting point for this study was an observation of a seasonal eddy in the Juan de Fuca strait that appeared over a narrow canyon. From a more general point of view, we wish to study the effect of narrow canyons on overlying geostrophic flow and how canyons might act as efficient conduits for water.

These dynamics are being considered with a numerical model and with simple analytical models. The analytical models are used to understand the important parameters and the dynamics, while the numerical model is used to solve for situations with complicated canyon topographies.

To date, the analytical models have considered an unstratified fluid, having a cosine spatial dependence flowing over a straight canyon. If the canyon is narrow and extends completely across the flow domain, then the steady solution is a flat surface over the canyon, and no flow across the canyon. If the canyon, however has an end then the steady solution is that the free surface over the canyon is flat and the geostrophic flow distorts to flow around the canyon.

Analytical solutions show that the flow in the canyon responds quite rapidly, within a few hours, to changes in the overlying geostrophic flow. If the canyon is narrower than the radius of deformation by a factor of .88, then the cross-canyon flow, and hence the coriolis effects in the canyon, are negligible. That is the canyon obeys hydraulic and not geostrophic dynamics. Under these circumstances, the canyon pumps water in an attempt to level the free surface.

We have just obtained current meter records from Wunsch for the Hudson Canyon study to confirm some ideas on the nature of the circulation in a canyon. In particular, we are interested in the strong inertial oscillations that appear in the analytical and numerical solutions. We have inquired from two other sources for similar current meter data in and around canyons.

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1/1/86-12/31/86

Eric B. Kraus
Howard P. Hanson

**Dynamical Forcing of the Ocean
by
Transient Air-Sea Interaction Processes**

Summary

This project concerns the role of ocean-atmosphere exchange processes in forcing the general circulation of the oceans, particularly those processes that exhibit spatial and temporal dependence. The research involves modeling studies pertaining to formation and dissipation of ocean fronts in the subtropical Atlantic that are the subject of the forthcoming Frontal Air-Sea Interaction Experiment (FASINEX). The modeling will be conducted using a hybrid model recently developed by the P.I.'s in collaboration with Prof. R. Bleck (Univ. of Miami). Bleck's isopycnal ocean model (e.g., Bleck and Boudra, 1981 *J. Phys. Oceanogr.*) has been combined with a thermodynamically-active ocean-surface mixed layer model, which now replaces the parameterization of "surface" processes in the original isopycnal model. The annual cycle of an idealized mid-latitude ocean basin in response to imposed wind and thermal forcing has been simulated. These results will be fine-tuned, using an actual wind and temperature climatology for the Atlantic, and used as boundary conditions for a fine-resolution version of the model to be forced by wind and thermal fields observed during the FASINEX field phase (February, 1986). The sensitivity of the processes of frontogenesis and frontolysis in the model to variations in the forcing will be investigated.

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Contract Period: 1 February 1986 - 31 January 1987

W.G. Large

FASINEX WIND STRESS

A remote instrument package has been developed with NASA sponsorship, to measure surface wind stress from ships and buoys during the Frontal Air-Sea Interaction Experiment. Twenty minute averages of wind speed and stress are completed using the inertial dissipation technique and both transmitted to Service Argos satellite receivers and stored in local memory. At the heart of the stress computations is digital filtering with sixth order butterworth band-pass filters. Parallel processing is employed so that the mean wind speed, U , can be used to keep the filters stationary in natural frequency space, $n=fz/U$, where 'f' is frequency, and 'z' is the measurement height. Three filters span the ranges in 'n' of 0.25-0.50, 0.50-0.75, and 0.75-1.0 and since all these ranges are entirely within the inertial subrange, three independent stress estimates are obtained every twenty minutes. Since robust propellor wind sensors can be used the package is suitable for unattended operation.

With ONR support, Sea Data Corporation has produced new versions of their WOTAN (Weather Observations Through Ambient Noise) instruments, which measure subsurface acoustic noise in 12 frequency bands between 2 and 25 kHz. One such unit has been installed at 150 meters depth below one of the FASINEX moorings. In collaboration with David Farmer, an identical unit will be deployed from R/V Endeavor in a rapid sampling mode. It will be suspended along with an inverted echo sounder and video camera, below a free drifting buoy for up to 8 hours. Here the role of wave breaking in sound production will be studied.

During FASINEX wind stress will also be measured by Ken Davidson and an excellent wind velocity field will be measured at the five surface moorings. In addition, microwave backscatter measurements (scatterometry) will be made from aircraft from NASA and the Naval Research Laboratory. Both scatterometry and WOTAN provide remote indirect estimates of the wind, which may be more closely related to the stress than to the velocity and the FASINEX data set will be used to investigate this question.

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10 October 1984-31 September 1986

Kevin D. Leaman

RECIRCULATION AND GULF STREAM DEVELOPMENT
NORTH OF THE BAHAMAS

Results of three intensive, multi-year observational efforts in the Gulf Stream have been examined. The first two efforts were carried out by this principal investigator as part of the NOAA-funded STACS (Subtropical Atlantic Climate Study) program at 27°N and the DOI-funded FACTS (Florida Atlantic Coast Transport Study) program at 29°N. The third effort was carried out with ONR support by Dr. T. Rossby of the University of Rhode Island in the Gulf Stream off Cape Hatteras. In each experiment, CTD (conductivity-temperature-depth) instruments and ocean absolute horizontal current profilers (PEGASUS) were used to obtain repeated cross-sections of hydrographic properties (temperature, salinity, etc.) and absolute currents in the Gulf Stream. Results obtained by this principal investigator and Dr. Rossby are of sufficient interest that we are now preparing a joint paper for submission. For example, although the absolute Gulf Stream transport increases by a factor of three (from $30 \times 10^6 \text{ m}^3/\text{s}$ to $90 \times 10^6 \text{ m}^3/\text{s}$) from 27°N to Cape Hatteras, many of the properties of the internal structure of the Gulf Stream (such as the northward perturbation temperature flux) are remarkably similar at these two latitudes.

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Contract Period 10/01/84 - 09/30/86

Edward R. Levine

STUDIES OF FRONTAL MIXING IN THE GULF STREAM

The objectives of this research are to determine the dominant scales of water mass exchange and mixing along the Gulf Stream frontal boundary, to estimate fluxes of heat, salt, and tracers across the dynamical front, and to consider the relationship of these finescale processes to small scale mixing models and mesoscale motions. The approach is structured around the unique survey capabilities of the isopycnal Swallow floats (ISF), the instrumented SeaSoar (CTD/O₂), and the XCP current profiler. Following our development of the instrument (Rossby, Levine, and Connors, Prog. Ocean., 1985), deployment of the ISF has shown it to approximate three-dimensional water parcel motion and enable us to study of Gulf Stream kinematics along an isopycnal trajectory (Levine, Connors, Cornillon, and Rossby, JPO, 1986). Subsequently, a preliminary study of the entrainment of Shelf/Slope water just east of Cape Hatteras was conducted (Levine, Connors, and Cornillon, DSR, 1986, in prep.).

In Sept -Oct 1985 a major frontal mixing study of three regions along the Gulf Stream edge was completed. The primary sampling technique was the statistical/spectral method, horizontal transects with a sampling rate consistent with the scale of the phenomena. In this survey mode, ISF's defined the evolving structure of the event. Study regions included the upwelling region associated with the Charleston Bump, the entrainment region just east of Cape Hatteras, and the shingling region east of Cape Hatteras. Currently, analysis is proceeding, as well as a followup entrainment study.

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1/1/86 - 31/12/86

Murray Levine

ARCTIC INTERNAL WAVES

Time series of temperature and conductivity were obtained as part of the Arctic Internal Wave Experiment (AIWEX) which was conducted about 350 km north of Prudhoe Bay, Alaska, during March and April 1985. The main purpose of this project was to determine the spectrum of vertical displacement associated with the internal wave field. Historical evidence has suggested that the internal waves in the Arctic may be significantly different from the "universal" description of the Garrett-Munk model (Levine, Paulson, and Morison, JPO, 1985).

A total of 13 temperature and 5 conductivity sensors were deployed spanning depths from 80 to 500 m and horizontal separations from 150 to 1000 m. Data were recorded every minute for 35 days.

Preliminary results indicate that the Arctic internal wave spectra are strikingly different from lower-latitude observations:

- the internal wave energy is significantly lower, and
- the spectral slope is substantially less steep, with a $(\text{frequency})^{-1}$ dependence.

Further analysis exploring the time dependence and coherence structure of the wave field is continuing.

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1 November 1985 - 21 October 1986
(Combined UPPER OCEAN/ARCTIC INTERNAL WAVES)

R. G. Lueck

Ocean Turbulence

The long range goal of ocean turbulence research is to determine the role of turbulence and other microstructure in the circulation of the ocean and in the vertical flux of momentum, heat and salt. The rate of dissipation of turbulent kinetic energy will be estimated from vertical profiles made in the California current system during the 1982 DOLPHIN cruise and profiles collected during the MILDEX (Mixed Layer Dynamics) Experiment. Data from the DOLPHIN trip will be used to compare the horizontal and vertical signatures of microstructure and to examine mixing at the boundaries of intrusions. Time series at fixed locations always show one or more layers that remain turbulent for up to 24 hours. The data will be used to examine the temporal variability of turbulent layers. The DOLPHIN data is being analyzed with Dr. Yamazaki. The MILDEX data spans the rising edge of a storm and will be used to study the response of the mixing layer, to make a mixing layer budget, and to examine the delayed growth of turbulence in the thermocline. We will also participate in the analysis of some of the data taken with the USS DOLPHIN during the cruises in April and Fall of 1984. Our effort will concentrate on the mixing layer-thermocline interface measurements. We will also continue development work on the air-foil probe including an examination of the usefulness of the newly developed piezo-electric films.

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JOHN L. LUMLEY

MODELING OCEAN TURBULENCE

Use of computational modeling, experimental data, and theoretical analysis to characterize, parameterize and model near-surface fluxes (in water and air) of latent and sensible heat, salt, gases, droplets and momentum and the interdependence of these fluxes, as well as wind-wave interaction, wave-turbulence interaction, and the dynamical effect of all these on the turbulent transport. A number of recent papers have appeared, e.g.: Kitaigorodskii, JPO 1983, 1984a, b; Kitaigorodskii & Lumley, JPO 1983; Kitaigorodskii, Donelan, Lumley & Terray, JPO 1983; Lumley & Terray, JPO 1983.

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7/1/82 - 6/30/84

James R. Luyten

EXPLORATION OF THE AGULHAS RETROFLEXION

The Agulhas Current system is the western boundary current for the gyre of the south Indian Ocean, flowing poleward along the coast of southern Africa. This current, together with its associated recirculation and eddy field, is the most energetic feature in the southern hemisphere both in terms of its air-sea interaction and mesoscale variability. Nearly all that is known about the Agulhas has come from the analyses of hydrographic and CTD observations and satellite imagery. While this is a rich and varied set of data for interpretation and speculation, there are few direct observations of the current field per se.

To explore this current system, particularly the region where the Agulhas has separated from the coast and turns eastward again--the Retroflexion, we deployed a long-term large scale mooring array. The array consists of 10 moorings, deployed for two years, with current meters at 200, 750, 1500 and 4000 meters depth. The moorings extend from the region where the current separates from the continental shelf to the southwestern end of the Retroflexion region. The moorings are scheduled for recovery in early 1987.

On the deployment cruise in early 1985, a detailed quasi-synoptic survey of the path of the Agulhas was obtained with XBTs. In conjunction with J. Toole at WHOI a large scale CTD survey of the region was carried out. Surface drogued buoys were deployed both in the current and in several Agulhas rings in collaboration with D. Olson (Miami). These observations are currently being analyzed and will be integrated with the moored data and satellite imagery (Luyten/Chase).

Theoretical work on the nature of combined wind and buoyancy forced circulations in simple gyre-scale analytical models is continuing with Henry Stommel. The models are being extended to include the effects of relative vorticity, and it is hoped that they can be applied to the Agulhas current system to explore the Retroflexion process.

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January 1, 1986 - December 31, 1986
January 1, 1987 - December 31, 1987

James R. Luyten & Robert R. P. Chase

ANALYSIS OF SATELLITE IMAGERY FROM THE AGULHAS RETROFLEXION

Much of the historical information of the structure of the Agulhas current, its path and variability has come from analyses of the satellite imagery. The formation of the large rings within the Retroflexion region, and the speculation that the progression to the west of the retroflexion itself until ring formation has been based almost entirely upon the satellite imagery.

The recent work by Gordon (LDGO), Toole (WHOI), Olson (Miami) and the moored work by Luyten provide a much larger data set of direct observations of the Agulhas current system which needs to be integrated with the historical data. The contemporaneous satellite imagery, particularly the NOAA-7 AVHRR data, can provide a connection between recent data and the historical observations.

The AVHRR images have been recorded by the Remote Sensing Center in Pretoria, transferred to the Remote Sensing Vax Processor in Woods Hole for analysis. The images have been navigated and registered, and the analysis of the kinematics of the surface temperature field has begun. Detailed comparisons with the other available observations will be made as the data become available.

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January 1, 1986 - December 31, 1986

Lorenz Magaard

ANALYTICAL MODELING OF LOW-FREQUENCY
PROCESSES IN THE NORTH PACIFIC

The objective of this program is to study low-frequency processes at the surface and in the interior on the midlatitude North Pacific based on long oceanic and computer-simulated temperature (or geostrophic stream function) records.

TRANSPAC DATA: In our work on these data we had shown that the fluctuations in the western half of the North Pacific (contrary to those in the eastern half) are not dominated by neutrally stable Rossby waves. Our investigation to what extent the regional variability of the statistical characteristics of the observed fluctuations can be explained in terms of local baroclinic instability or radiating instability of the nonzonal mean flow is still going on.

The other oceanic data studied under this program are the long time series of isopycnal displacements at OWS P and along Line P. We have shown that the fluctuations in the 3 to 8 year period range are dominated by first shear mode baroclinic Rossby waves. In the western half of Line P (towards OWS P) waves with periods from 6 to 8 years dominate. In the eastern half (towards the coast) shorter period (3 to 6 years) waves prevail. Preliminary studies of the generation of these waves show evidence that they are not generated by local or coastal wind fluctuations.

Besides our studies on oceanic data we are working on two computer-simulated data sets from a region simulating a portion of the MODE area (obtained from Dr. Robinson, Harvard) and from the North Pacific obtained from Dr. Haney, NPS). We are analyzing these data with respect to Rossby waves with the idea to learn about their generation and predictability. We are presently concentrating on the Haney-data which are more suitable to study wave generation. First results indicate significant differences between Rossby wave features in the real ocean and the Haney-model. It is too early to draw general conclusions. The Robinson-data are suitable to study the predictability of Rossby waves. Our studies on these data have just begun.

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March 1, 1985-February 28, 1986

Tony Maxworthy
Frederick Browand

TURBULENCE IN ROTATING AND/OR
STRATIFIED FLUIDS

Overall Scientific Objectives: To understand through laboratory experiments, theoretical analyses, and comparison with field data, the processes by which turbulence in the world's oceans is generated, evolves and decays.

Methodology: Laboratory studies are judiciously chosen to illustrate fundamental processes. Efforts are made to relate the results of laboratory studies to the ocean environment.

Recent Results: Experiments with towed grids and oscillating grids have explored the structure of a turbulent front in a stratified fluid. Stratification begins to affect turbulence structure at a non-dimensional time $Nt \approx 2.0$. (Time t is measured from initiation of motion, and N^{-1} is the intrinsic fluid oscillation frequency.) Vertical scales in the turbulence are limited by the Ozmidov scale, and the front evolves into a series of intrusions for $Nt > 10$. By $Nt \approx 30$, most of the energy is concentrated in these intrusions, which in planform, resemble pancake eddies. Eddies lying in different horizontal planes are only weakly coupled (possibly by internal waves), but those lying in the same horizontal plane eventually amalgamate to form larger eddies. Eddy behavior is primarily inviscid, and should be observable at oceanic scales. The relationship between laboratory results and quasi-2D oceanic eddy fields is presently being explored in detail. Our laboratory studies have shown that evolving fronts have a fractal dimension. The same technique applied to a sequence of satellite images of upwelling along the California coast results in a dimension of 1.4. The relationship between fractal dimension and frontal dynamics is not yet understood.

Related laboratory observations have shown rotation to dramatically decrease turbulent mixing and entrainment across a density interface. Rossby numbers in the experiments lie in the range of 1 - .2. The reduction in mixing is thought to be a result of the generation of inertial waves at the interface. These waves extract energy which would otherwise be available for turbulent mixing, and provide a possible explanation for the longevity of mesoscale oceanic eddies which often have lifetimes measured in years.

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Contract Period: 12/01/85 - 11/30/86

M. S. McCartney

GENERAL CIRCULATION AND FORMATION OF WATER MASSES
IN THE ATLANTIC OCEAN

The objective of this project is to increase our knowledge and understanding of the general circulation of the Atlantic Ocean. A main focus has been on the influence of subpolar deep convection on the water masses of the thermocline and the deep water. The tools used are traditional hydrographic ones: core layer and isopycnal analyses and dynamic computation of velocity fields. An additional powerful new tool is pycnostadal analysis: the use of potential vorticity distributions to infer sources and circulations of water masses. Studies completed during the contract period are: (1) the influence of convection west of Ireland on the thermocline of the North Atlantic subtropical gyre; (2) the abyssal circulation of the eastern North Atlantic Ocean; (3) a large deep western boundary current of the tropical North Atlantic. The main effort during the remainder of the contract period will be on three inter-related studies: (4) the deep western boundary current of the tropical North Atlantic; (5) the transposed Antarctic Bottom Water of the western North Atlantic; (6) geostrophy in the abyss of the equatorial Atlantic.

A set of four lines of CTD stations off the coasts of Brazil and Uruguay was collected in late 1984, at the beginning of the current contract period. Calibration and editing of these data are complete, and analysis is underway. The initial studies involve comparisons of the baroclinic field of the Brazil Current and its recirculation to the Gulf Stream system, with the goal being a more quantitative characterization of their differences than the old idea of a "big" Gulf Stream and a "small" Brazil Current. This will be accomplished by examining the transport field as a function of depth, density (water mass) and down stream coordinate. A related comparison of the subpolar boundary currents (Falkland and Labrador) and their influence on their neighboring subtropical gyres will be made.

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October 1, 1984 - September 30, 1986

J.P. McCreary and P.K. Kundu

CIRCULATION ALONG OCEAN BOUNDARIES

We are presently involved in two studies of coastal circulation that are nearing completion. The first one is a study of the circulation at an eastern boundary driven by a poleward increase of near-surface density. The resulting sea level slopes downward toward the pole in the ocean interior, and there is an associated eastward geostrophic current. This interior current forces downwelling at an eastern boundary, and generates both a poleward surface current and an equatorward undercurrent. For realistic choices of model parameters the coastal circulation is as strong as, and opposite in direction to, that caused by a typical equatorward wind stress. Our solutions compare remarkably well with observations of the Leeuwin Current off the west coast of Australia, suggesting that it is forced by surface density gradient. This work is in press in the Journal of Marine Research.

The second problem that we are working on the circulation forced by an inflow of water through an eastern ocean boundary. Without vertical mixing the inflow continues across the ocean. With vertical mixing, however, part of it bends poleward to generate a coastal undercurrent. Solutions suggest that the southward bending of the throughflow from the Pacific into the Indian Ocean may contribute to the Leeuwin Current off western Australia, but that it is not the dominant mechanism for driving the circulation there.

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Contract Period: Nov. 1, 1984 - Oct. 31, 1985.

Robert N. Miller

Numerical Modeling of Synoptic Scale Ocean Dynamics

The principal objective of this work is the efficient implementation of statistically optimal data assimilation schemes, i.e. methods for the combination of observed data with model output, and theoretical questions which arise in this context. Current emphasis is on the application of the Kalman filter to realistic models for use with real ocean data. The Kalman filter is a data assimilation method which has been widely used in a variety of engineering problems. Its desirable features are optimality in the least squares sense for a broad class of systems and the ability to assimilate data of varying types, distributions and error characteristics. A pilot study using the Kalman filter with a simplified model and synthetic data has been completed (Miller, JPO, 1986) with encouraging results.

Theoretical work on the consequences of imposing computational boundaries on model regions where no physical boundaries exist ("open-ocean simulations") is nearing completion. The nature of the irregularities which can arise at points where the flow is tangent to the model region is now understood, at least qualitatively, and computer simulations are being carried out.

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CHRISTOPHER N.K. MOOERS

OPTOMA (OCEAN PREDICTION THROUGH OBSERVATION, MODELING,
AND ANALYSIS) PROGRAM

OPTOMA, a joint NPS/Harvard program with participation by OSU, is taking the initial steps in real-time, four-dimensional data assimilation for the description and prediction of synoptic/mesoscale variability in open ocean domains. The goals are (1) to determine the scientific limits of practical, open ocean mesoscale forecasting, and (2) to advance our understanding of the mesoscale kinematics, dynamics, and energetics in the California Current System (CCS). Over the past four years, quasi-synoptic surveys and ocean prediction experiments have been conducted in a 200 x 200 km domain (called NOCAL) centered about 200 km offshore from Point Arena (N. California) in the CCS. The basic scheme for 4-D data assimilation, called the Ocean Descriptive/Predictive System (ODPS), is based on an observing system plus statistical (objective analysis (OA)) and dynamical (quasi-geostrophic (QG)) models.

The kinematical description of the CCS has been updated (Mooers and Robinson, SCIENCE, 1984 and Rienecker, et al., JGR, 1985). A new understanding of the CCS as a system of meandering turbulent jets, often close-packed cyclonic and anticyclonic synoptic/mesoscale eddies, and nearsurface thermal anomalies and fronts has emerged. This new description helps to interpret satellite imagery more fully and to infer cross-shore transport of properties over a few hundred kilometers in a week or so. Studies of local dynamics and energetics are in their early stages.

OPTOMA performed a prototype, real-time ocean prediction experiment (OPTOMA5) for a month in the summer of 1983 and a full, real-time ocean prediction experiment (OPTOMAll) for two months in the summer of 1984 in NOCAL. Forecast experiments from OPTOMA5 (Robinson, et al., NATURE, 1984 and Robinson, et al., JPO, 1986) dynamically interpolated between maps to define the evolution of mesoscale features under the dominant influence of internal processes. During OPTOMAll, boundary forcing was more influential. The longer observational period for OPTOMAll allowed improvement of the statistical model. Forecasts, as well as forecast experiments, have been performed. These experiments involved shipboard quasi-synoptic surveys using XBT/CTD casts, an airborne synoptic survey using AXBTs, and satellite AVHRR imagery. The ODPS was used in real-time at NPS and Harvard. The OA model is used routinely at sea. An Airborne Digital Data Acquisition System (ADDAS) has been developed, deployed, and documented (in an NPS Technical Report (Colton and Mooers, 1985)); ADDAS provides an "air casting" capability using the OA model. The prediction experiments have been supported by eight additional (total of nine maps so far in NOCAL plus CENCAL) airborne and 22 additional (total of 28 maps so far in NOCAL plus CENCAL) shipboard mappings which provided additional information for model development and an improved description of the regional synoptic/mesoscale fields. The continuing mapping efforts led to the fortuitous documentation of a large subsurface, offshore temperature anomaly associated with the 1982/83 el Nino (Rienecker and Mooers, JGR, 1986). A few more shipboard mappings and several more airborne mappings are planned in FY86. In September 1984, OSU installed three current meter moorings,

each with five current meters, which were recovered from NOCAL in July 1985. The primary objective of this effort was to determine the synoptic/mesoscale barotropic component of flow, and its relationship to the baroclinic component, in order to evaluate and modify, as necessary, our model initialization procedure. Analyses, for this objective and related studies, are in progress.

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1 October 1985 to 30 September 1987

DYNAMICS OF SMALL-SCALE OCEANIC MOTIONS

This project aims at the understanding of the fundamental processes which govern the dynamics of small-scale oceanic motions. The work is basically of a theoretical nature, including data analysis and numerical modelling. Two specific phenomena or processes are studied: small-scale vortical motions and the interaction between the surface mixed layer and the ocean interior.

Small-scale vortical motions

The vortical mode of motion carries the potential vorticity of the flow. At large and meso-scales it represents geostrophic and quasi-geostrophic flows. Vortical motion must also be expected to exist at small scales, in addition to internal gravity waves which do not carry potential vorticity. The energy and shear content, the dominant space and time scales, and the dynamics of small scale vortical motions are not known. To develop a basic understanding of these motion and their role in oceanic processes, this project analyses existing data sets for vortical motion, studies theoretically the interaction between vortical motion and internal gravity waves, and assesses the requirements and feasibility of an experiment that will unambiguously determine the kinematic structure of small-scale vortical motions.

A major effort of the project is the analysis of the IWEX and MILDEX data sets for vortical motion. The three-dimensional nature of these data allows the direct estimation of the frequency spectrum of potential vorticity (or the vortical mode) at various horizontal scales ranging from about 2 km to 6m. These estimates will be used to hypothesize a complete wavenumber-frequency spectrum of the vortical mode.

Intraction between the surface mixed layer and the ocean interior

The long term goal of this project is to couple a bulk mixed layer model with an ocean interior model. A coupled model will provide a better description and prediction of the near surface thermal and current field. Various algorithms for such coupling have been suggested and applied. This project's approach is to identify and parameterize the actual exchange processes between the surface mixed layer and ocean interior. Specific processes under investigation are the effect of vertical advection on entrainment and mixing and the parametric instability caused by a time varying background stratification.

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03/01/86 - 02/28/87

LONG PERIOD WAVES AND CURRENTS

L. A. Mysak

1. Modon dynamics

Two aspects of the theory of barotropic modons (quasi-geostrophic vortex pairs) have been investigated. First, necessary instability conditions have been derived in the form of integral constraints involving the modon wave number. In particular, for eastward-travelling modons, the integral constraint is consistent with the numerical results of McWilliams et al. (Dyn. Atmos. Ocean, 1981). A second class of problems studied involves the application of the method of multiple-scales to modon propagation in slowly-varying media. In particular, the decay of the modon radius and translation speed due to a weak bottom Ekman boundary layer has been determined (Swaters, JPO, 1985). Also, the evolution of a modon over slowly-varying topography has been investigated.

2. Eddies and Rossby waves off the South African Coast

The retroflection region of the Agulhas current, about 500 km south of Cape Town, is an active generation area of eddies and wave-like features that are frequently observed to the west, in the South Atlantic Ocean (e.g., "Eddies in Marine Science" 1983). Mechanisms currently being investigated which may help to explain these transients include the generation of waves and eddies by an oscillating vorticity source concentrated in the retroflection region, and by the annual cycle of the windstress curl. For the latter problem the numerical model of Cummins, Mysak and Hamilton (JPO, 1986, in press) is being used.

3. Mean flow effects on annual Rossby waves in the North Pacific

To study the effects of the subtropical mean gyre on annual Rossby waves in the central North Pacific (e.g., White and Saur, JPO, 1981; Cummins et al, JPO, 1986), an ocean general circulation model is being developed. It is a three-layer, quasi-geostrophic model in spherical coordinates which will be spun up using the climatological mean winds. From this model, a limited area circulation model of the eastern central Pacific Ocean will be developed and later used for the Rossby wave studies.

4. Scattering of Rossby waves by a geostrophic front

Annual period Rossby waves that are generated by the windstress curl off the Oregon-Washington coast propagate their energy to the south-west (Mysak, JPO, 1983, Cummins et al., JPO, 1986). Such waves will encounter the subtropical front, located at approximately 32°N, and thus will be subject to reflection and/or absorption by this feature. Using the recent frontal geostrophic model of Cushman-Roisin (pers. comm. 1985), I propose to investigate this wave scattering problem using a multi-layer ocean model.

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1 February 1986 - 31 January 1987

Pearn P. Niiler

UPPER OCEAN CIRCULATION OF MIXED LAYER DRIFTERS

A new satellite-tracked drogue system has been designed, built and tested for obtaining ARGOS fixed Lagrangian trajectories and temperatures in the ocean mixed layer (with R. Davis and H. White). Its virtues are a 200/1 drogue-to-surface float drag area ratio, non-sailing character of the drogue (shape of a radar corner reflector) and total symmetry of surface floats (fiberglass spheres) to reduce directional wave forces. There needs to be no relative flow to keep the drogue deployed and no heavy weight to keep it oriented into the flow. The entire system is painted with anti-biofouling agent and self-deploys from a mooring ship. In July 1985, 20 of these were released in a study of CALIFORNIA CURRENT FRONTS. Eighteen are still reporting on a regular basis 8 months later (5 reports a day on the average, compared with 6 possible ARGOS receptions south of 30°N latitude). The water-following capability of the system in six different wave states and mixed layer shear was tested by placing a VMCM on top and bottom of the drogue. Drogue "slip" of .06-2.4 cm/sec in significant wave height of 0.3-2.2 m and mixed layer shear of 1-36 cm/sec was recorded. Analysis of the drift data shows the California Current, south of the 32°N latitude, to be composed of a series of eddies interspersed with strong filamented southward flows. Tests in North Pacific winter conditions will be carried out in Fall 1986 in preparation for deployment of arrays of mixed layer drifters in OCEAN STORMS experiment in Fall 1987. The principal science objectives of OCEAN STORMS (ed. E. d'Asaro, U. of Washington, Nov. 1985) is to document the three-dimensional response of the upper ocean to Gulf of Alaska storms on horizontal scales of 10-300 km. The principal objective of the ARGOS drifter development project is to provide a low-cost, multi-year drifter of known water following characteristics for study of large-scale Lagrangian flow in the upper ocean.

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10/1/85 - 9/30/87

Doron Nof

MESOSCALE PROCESSES IN THE OCEAN

I. Objectives

The present contract focuses on the dynamics of isolated eddies, the behavior of outflows and the generation of shock waves. The studies are theoretical; models are developed with the aid of analytical or quasi-analytical models. The main objective is the development of nonlinear models for mesoscale processes such as Gulf Stream rings and straits and passages (e.g., the Tsugaru Strait).

II. Major accomplishments

i) Development of a model describing the collision of the Gulf Stream with warm-core rings. This model introduces a new concept in ring-Stream interaction. It illustrates the mechanism by which Gulf Stream water envelops warm-core rings. It also demonstrates the resulting re-absorption of warm-rings by the Gulf Stream. ii) Development of a model describing the merging of isolated eddies. This model illustrates how two lens-like eddies must merge if some mean flow causes them to touch each other. The results of the model are verified in a simple laboratory experiment which uses a Freon-silicone oil mixture to form the eddies. iii) Examination of the atmospheric cooling of warm-core rings and the associated spirals. iv) Determination of shock waves behavior in channels and straits. The purpose of this study is to examine the possibility that the abrupt and violent changes observed in several straits and passages can be explained in terms of discontinuities (in the physical properties) which behave in an organized manner. In particular, attention has been given to what we have termed "geostrophic shock waves." These are shock waves whose adjacent flows are exactly geostrophic in the cross-stream direction. They contain a mechanism which can significantly increase the potential vorticity of the fluid. v) Examination of outflows spreading in wedge-like basins. This study focuses on the cases where the oceanic basin is very broad and the land mass resembles a "delta." Under such conditions, the outflow bifurcates and forms two distinctly different currents.

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4/1/85 - 3/31/87

Worth D. Nowlin, Jr.
Thomas Whitworth III

Studies of the Stratification and Circulation of the South Atlantic

Our overall research goal is a better understanding of the general circulation of the South Atlantic Ocean. A principal data source is the Long Lines data along the Greenwich Meridian and in the Scotia Sea. Other recent data sets and the historical data base are also being used to document the changes imposed on the characteristics of the Antarctic Circumpolar Current (ACC) by the introduction of North Atlantic Deep Water in the southwest Atlantic.

Water characteristics in the South Atlantic derive in part from interactions among the subtropical and subpolar gyres and the ACC. Much of this activity takes place in the southwest Atlantic--eastern Scotia Sea-Georgia Basin region. Recently acquired data near the Falkland Plateau will be analyzed in conjunction with historical data to study the frontal structure in this region. The paths of the Subantarctic Front/Falkland Current and the Polar Front as they enter the open South Atlantic from the Scotia Sea will be examined. Of potentially great importance to the ventilation of South Atlantic waters is the Weddell-Scotia Confluence. The nature of this front, and its possible relationship to the Continental Water Boundary-Scotia Front will be further studied.

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Contract period: 1/1/86 - 12/31/86

James J. O'Brien

VARIATIONAL DATA ASSIMILATION

James J. O'Brien

It is now recognized that oceanographers will never have the data base to initialize large scale ocean models such as done for the atmosphere. Hence there is great interest in techniques for data assimilation. The usual oceanographic approach is called "The Inverse Method" which has been used by Professor Wunsch and his disciples to estimate the mean state of the ocean's general circulation.

The approach advocated by the P.I. is somewhat different. It follows the school developed by Professor Sasaki who advocates the use of "Strong Constraints for Time-Dependent Data Assimilation". The technique uses the methods of variational calculus. Suppose we have a set of partial differential equations, $L_i(q_j, c_k) - F_i = 0, i = 1(1)I$ where q_j are the dependent variables: $c_k, k = 1(1)K$ are adjustable parameters and F_i are forcing functions such as the wind stress field. This set of P.D.E.'s with appropriate boundaries represents an ocean model. In addition we have a limited set of observations, q'_j , which may be very sparse in space and time; we have estimates of the parameters, c'_k , and estimates of the wind stress and other forcing fields F'_i as a function of space and time. A variational function of q_j, c_k and F_i can be specified so that the error between these variables and their estimates is minimized. In this method, the model equations themselves become part of the variational function. The method greatly expands the number of equations, but they can be solved iteratively on a large-scale computer.

These concepts are being implemented in a series of upper ocean models for data assimilation. This is an exciting new research area with great promise for advancing ocean modelling.

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Contract Period

October 1, 1985 to September 30, 1989

James J. O'Brien

INDIAN OCEAN MODELLING

Mark E. Luther and James J. O'Brien

We are developing a series of numerical models of the wind-driven circulation in the Indian Ocean. The model (often called a reduced gravity model) consists of a single thin, dynamically active upper layer over a cooler, deeper, motionless lower layer. The present version of the model covers the western Indian Ocean from 10°S to 25°N and from 40°E to 75°E, and is being expanded to cover the entire Indian Ocean to the north of 25°S from Africa to Australia and Indonesia. The model uses several different observational wind data sets as forcing. Different model cases have used forcing derived from a monthly mean climatology (MMC) of ship winds, from the surface level winds from the First GARP Global Experiment (FGGE) of 1979, and from a 23 year long data set of monthly mean ship winds which extends from 1954 through 1976. The cases using the MMC and FGGE winds are run in a seasonal mode, with the same year-long wind cycle repeated for several years. After a brief spin-up phase, the circulation patterns develop a regular seasonal cycle with nonlinear eddies repeating from one year to the next. These model cases are described in Luther and O'Brien (1985, Prog. in Oceanogr., 14, 353-385) and in Luther, O'Brien and Meng (1985, Coupled Ocean-Atmosphere Models, Ch. 27, J.C.S. Nihoul, ed.). The 23 year integrations are run in an interannual mode, after a three year spin-up using the monthly mean winds over the 23 years. We are now investigating the interannual variability in these current patterns, and the correlations between the variability in the circulation patterns and monsoon variability or El Niño/Southern Oscillation variability. The same general circulation features appear year after year, but the strength, position and timing of these features vary considerably over the 23 years.

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Contract Period

October 1, 1985 to
September 30, 1989

Donald B. Olson

THEORY AND OBSERVATIONS OF OCEAN FRONTS

Present activities include data collection and analysis in the South Atlantic Ocean with surface drifters and satellite data. The drifters were deployed as part of two experiments in the Agulhas Retroflexion and a three cruise effort in the Brazil Current and its extension. The drifter and satellite sea surface temperature (SST) time series are augmented with diagnostic models using historical hydrographic data and synoptic data taken by other investigators in the Southern Ocean Studies Initiative (SOS).

Results range from a gyre scale description of fronts and their eddy fields from a diagnostic model using historical data, 109 drifter trajectories (89 FGGE units plus 20 SOS units), and a five year satellite SST series at two week intervals to synoptic studies of rings using ship, drifter, and high resolution satellite data. Two anticyclonic rings from each of the western boundary currents have been studied and compared to those from the Gulf Stream and boundary currents in the Pacific. The Agulhas rings are the most energetic reported in the world ocean by a factor of two. The two Brazil Current rings and a cyclonic ring formed from the Malvinas are somewhat surprising in that they are as energetic as their Gulf Stream counterparts although they are formed from current systems nearly ten times weaker than those in the North Atlantic. Part of the reason this is possible may be tied to the energetic recirculation cells tied to stationary Rossby-like modes observed in the Brazil Current extension.

Satellite and drifter data suggests these 400 km scale waves are stationary on time scales of two to six months while their creation and decay lead to ring formation and north/south excursions of the separation of the Brazil Current from the coast of four to five hundred kilometers. These excursions of the Brazil Current's separation have a significant annual component with southward extensions occurring in the December through March time frame. An analytic model of a finite amplitude Rossby wave train damped by lateral eddy viscosity is being used to understand the dynamics of the stationary waves in the Brazil and other western boundary currents.

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Contract Period 10/01/84 - 09/31/86

Thomas R. Osborn

Turbulence Measurements and Analysis

The submarine Dolphin has been instrumented to measure turbulence along predominantly horizontal transects. Measurements of the mean shear (with a Doppler acoustic profiler) and the density field (from a CTD) are also collected. Measurements in the fall of 1984 included acoustic scattering measurements by Farmer's group from IOS, Pat Bay and biological sampling by Haury of SIO. We believe the fall 1984 data include the generation of an inertial event by the wind and that analysis will show the turbulence related to the shear of that feature. Analysis of these data are underway.

The horizontal motion of the submarine makes it eminently suitable for detecting salt fingers. Measurements reveal fingers at values of R_p as large as 18, with fingers frequently seen at values between 4 and 6. These values of R_p are well removed from the region of fastest growth. Salt fingers may well be a ubiquitous feature when the local temperature and salinity fields are appropriate. Data collected where the mean temperature and salinity profiles do not favor fingering but where finger do appear on intrusions due to lateral gradients, show the buoyancy flux in the fingers is comparable but opposite to the mean turbulent flux. Analysis is underway for the data collected in 1982 off San Diego just above the salinity minimum to determine the relative importance of fingers in this region where the mean gradients allow fingering.

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Contract Period
1 November 1985 to 31 October 1986

A Theoretical Study of the Agulhas Current Retroflection

by Hsien Wang Ou

With the collaboration of W. De Ruijter, a two-layer model is constructed to examine the separation of an inertial boundary current from a curved coastline and its subsequent path as a free jet. In this model configuration, the separation occurs when the interface outcrops and forms a free streamline. Besides the constraint imposed by the coastal boundary, it is found that the primary dimensionless parameter that regulates the separation point and the subsequent current path is the scaled volume flux of the current (Q). Increasing Q causes the current to separate at a lower latitude. The separation also occurs where the coastline has a large positive curvature (i.e. convex outward). After the separation, the current can either meander or loop back on itself depending on the flow direction at the separation point. We have applied the model to the Agulhas Current and are able to reproduce the retroflection feature (i.e. a current turning back on itself) with roughly the correct dimensions. This suggests that we have isolated the essential physical mechanisms that can explain the retroflection phenomenon. The study has resulted in a paper published in the Journal of Physical Oceanography (January, 1986).

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Contract period: 10/1/85-9/30/86

W. Brechner Owens

EXPLORATION OF THE NORTH ATLANTIC CURRENT
AND ITS RECIRCULATION IN THE NEWFOUNDLAND BASIN

One area of the North Atlantic Ocean which has not yet been explored using direct current measurements is the Newfoundland Basin. This region includes the North Atlantic Current (the northern and eastward extension of the Gulf Stream) and is one of importance and controversy in various schemes describing the North Atlantic mean circulation. Twenty SOFAR floats and five Autonomous Listening stations (ALS's) used to track the floats will be launched during a May-June, 1986 cruise of the R.V. Endeavor. The first deployment of the ALS's is for 18 months. Anticipated results include a flow visualization of the North Atlantic Current examining issues such as flow over the Mid-Atlantic Ridge versus possible recirculation within the Newfoundland Basin. Maps of the mean flow and eddy kinetic energy are also expected.

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1 October 1984 - 30 September 1986

W. Brechner Owens and Bruce A. Warren

LARGE-SCALE CIRCULATION:
DEEP NORTHERN-BOUNDARY CURRENTS IN THE NORTH PACIFIC

We are attempting to describe the deep northern-boundary currents off the North Pacific on the basis of observations made during 1981-82: a line of year-long current measurements extending southward from the Aleutian Islands along Long. 175°W, and CTD sections extending southward from the Aleutians along Longs. 165°W, 175°W, and 175°E. One current flows westward along the Aleutian Island Arc and appears to be the recirculation boundary current required by deep-circulation theory. The other, lying immediately to the south, flows eastward, and appears to be a concentration of interior flow forced at least in part by the topography of the Aleutian Rise.

We had hoped that water-property contrasts would distinguish these two currents, and provide independent means for mapping them, but our deep regional correlations of salinity, oxygen, and nutrients against potential temperature are so tight that potential temperature in our area of study specifies all the other properties virtually within measurement error. We have therefore limited our mapping to potential temperature. However, using all available data at NODC north of Lat. 40°N between Asia and North America, we are finding that this pair of currents can be identified along the entire northern boundary of the North Pacific (though somewhat distorted as they cross the Emperor Seamount Ridge), and as far south as 40°N along the western boundary of the North Pacific.

A preliminary report on our results was published in 1985 in Progress in Oceanography, Vol. 14. Unambiguous evidence for geothermal heating of bottom water in the North Pacific, based in part on some of our data, has been reported in a manuscript by T. Joyce, B. Warren, and L. Talley, submitted to Deep-Sea Research. Work is in progress on a full account of our project.

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January 1, 1981 - September 30, 1986

Clayton A. Paulson

AIR-SEA INTERACTION (MILDEX, AIWEX)

As part of the Mixed Layer Dynamics Experiment (MILDEX), we towed a thermistor chain for a distance of about 1,000 nautical miles in various patterns approximately 300 miles west of Monterey, California. The data have been analyzed to determine the spatial properties of internal waves in the upper ocean as inferred from isotherm displacement. Wavenumber spectra agree with the Garrett-Munk (GM) model of internal waves, but values of vertical coherence are higher than predicted at wavelengths near 1 km. These results are consistent with upper ocean towed observations from many locations except N.E. of Scotland in Rockall Channel where spectral levels are a factor of three higher than GM.

Measurements made with a shipborne acoustic doppler velocity profiler during MILDEX are being analyzed in cooperation with Lloyd Regier. The analysis of exceptionally energetic inertial oscillations suggests that these oscillations are coherent over horizontal distances of about 100 km. We are proceeding with a combined analysis of the towed chain temperatures and acoustic doppler velocities in an attempt to estimate heat transports in the MILDEX area.

As part of the Arctic Internal Wave experiment, we made velocity measurements with current meters suspended from the ice. The experiment was conducted in spring, 1985, about 200 nautical miles north of Prudhoe Bay. Preliminary analysis of the observations indicates that spectral levels are about an order of magnitude below the GM model and the slope of the frequency spectrum is close to -1. Spectral levels at high frequencies increase following increased ice velocity and then decay after the ice velocity decreases. This suggests that internal waves may be generated by the motion of underice topography.

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1 Nov 1985 to 31 Oct 1986

1 Nov 1986 to 31 Oct 1987

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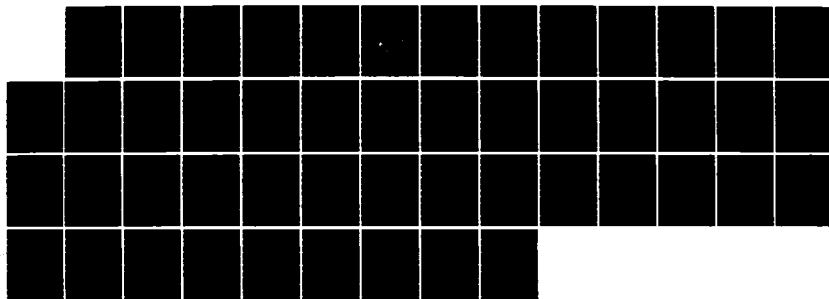
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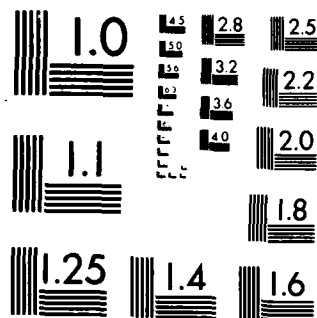
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Robert Pinkel

UPPER OCEAN PHYSICS PROGRAM FY1986

Efforts in this program center on analysis of data collected in the 1983 MILDEX experiment and on preparation for the Fall 1986 PATCHEX experiment. The data obtained in 1983 are from multiple Doppler sonars mounted on the research platform FLIP, as well as from a profiling CTD and numerous environmental sensors. The MILDEX information is being analyzed with emphasis on several specific issues. The basic energetics of the interval wavefield is being considered by R. Pinkel. R. Williams is studying the baroclinic tide. A. Plueddemann is estimating the wavefield anisotropy. J. Smith, R. Pinkel and R. Weller (WHOI) are investigating mixed layer flows using both direct sensors and Doppler scattering devices.

PATCHEX preparations include increasing the range and noise immunity of the existing sonars and doubling the CTD coverage (to 600 m every 3 min) from that of MILDEX. In addition, a small scale coherent sonar is being developed. This will have meter scale resolution. It will estimate velocity to 1 cm/sec precision on a second by second basis. The maximum range will be approximately 40 m. The coherent sonar will be lowered to depths of interest as indicated by the larger scale sonars and CTD. It will be used to monitor the development of unusual events in the shear field.

The PATCHEX experiment is planned for September and October 1986, off the coast of Southern California. We anticipate working from FLIP in close conjunction with Tim Stanton (NPGS) on the Cape Florida during the first several weeks of the operation, monitoring lateral and temporal variability in the mixed layer and upper thermocline. Later in the cruise we will be joined by Mike Gregg on the Thompson. The real time view of the large scale shear fields attainable with the FLIP Doppler sonar will be used to direct the sampling strategy of the Gregg and Stanton microstructure probes.

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1 October 1985 - 30 September 1986

Raymond T. Pollard

SEASOAR MEASUREMENTS DURING FASINEX

The Institute of Oceanographic Science's SeaSoar is about to be used in FASINEX (February 5-March 10). The SeaSoar, comprising a NBIS CTD in a body with adjustable wings, is towed behind a ship at 8-9 knots, profiling from 0 m to over 350 m every 1 to 2 km. Data from the resultant close spaced sections through the upper ocean are calibrated, corrected for salinity offsets, plotted and contoured on board ship to provide smoothed (reduced internal wave noise) sections with a few km resolution of temperature, salinity, density and hence pressure gradients and geostrophic velocity shear, within hours of data collection. Our observations of geostrophic shear will show its contribution to upper ocean dynamics (Pollard, Phil. Trans. Roy. Soc., 1983). Combination of SeaSoar data with Davis/Regier velocity profiler data will resolve ageostrophic flow. Repeated surveys will show the evolution of the frontal/mixed layer structure and variations of isopycnal depths. After careful calibration, temperature/salinity diagrams and contours of properties on isopycnal surfaces can distinguish water masses differing by as little as 0.02 psu (Pollard and Pu, Prog. Oceanog., 1985).

I am currently analysing SeaSoar, CTD and current data from two experiments, in late winter 1983 and 1984 northeast of the Azores. Both show that spatial variations in the mixed layer (up to 300 m deep) on scales from 3 to 300 km are predominantly caused by fronts and eddies. Even the diurnal heat budget of the mixed layer can only be explained by invoking convergent circulations. FASINEX gives the opportunity to set similar late winter observations in the context of a well-observed front.

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November 1985-October 1987

Lawrence J. Pratt

THEORETICAL AND NUMERICAL STUDIES OF
GULF STREAM MEANDERING AND EDDY DETACHMENT

Current and future research centers on the dynamics and predictability of Gulf Stream meanders and, in particular, on the detachment of meanders into rings and eddies. The work is proceeding on several fronts. First, the method of contour dynamics is being applied to study the detachment or 'pinching off' process by which rings are formed. Contour dynamics is a relatively new numerical method recently adapted by Pratt and Stern (JPO, 1986) for use in computing geophysical fluid flows. Second, a study is being made of a class of 'path equations' which describe the evolution of the Stream's path when the meanders have relatively small curvature. Because of their analytic simplicity the path equations yield general information more easily than do numerical simulations. Third, comparisons are being made between theoretical solutions and the actual Stream path observed over several weeks. The actual path is obtained from satellite imagery and the work is being done in collaboration with P. Cornillon and C. Gillman.

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FY86-87

James F. Price, Robert A. Weller
and Kenneth H. Brink

SURFACE METEOROLOGY

Our goal is to develop the instruments required to make long-term, unattended measurements of surface meteorological parameters from drifting and moored buoys. During this first year of the project (January 1986 to December 1986) we have focussed our effort upon measurement of relative humidity, and upon the recording device. This summer we will begin dockside tests of several promising humidity sensors (including chilled mirrors, and solid state devices) which will be repackaged to exclude liquid water. The tests are to determine the long-term stability and reliability of the sensors, as well as their suitability for buoy deployment.

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January 1, 1986 - December 31, 1986

Joseph L. Reid

WORLD OCEAN CIRCULATION

A major result of the current proposal has been the completion and publication of a study of the total geostrophic circulation of the South Pacific Ocean (Reid, 1986). I include here the abstract and the final figure.

Abstract — I have used the patterns of tracers (temperature, salinity, oxygen, silica, helium-3) and of density to estimate the geostrophic circulation (baroclinic plus barotropic) of the South Pacific Ocean at all depths. That is, the direction of horizontal flow is determined at all depths in a manner that appears to be consonant with the tracer patterns and that satisfies continuity of mass.

Within the upper kilometer the velocity shear is much stronger than at greater depths, and the baroclinic flow field alone is closely consonant with the tracer patterns except near the western boundaries. The barotropic components added to the baroclinic to provide a flow field that matches the tracer patterns in the deeper waters and to achieve continuity are quite small except in the western boundary currents, and only there do they provide a combined flow pattern significantly different from the baroclinic alone.

The resulting field of flow has equatorward deep western boundary undercurrents in each of the three basins and a poleward flow along the eastern boundary. A part of the Circumpolar Current follows the southern side of the East Pacific Rise around the Southeast Pacific Basin and then through the Drake Passage. The broad-ocean anticyclonic gyre of the upper waters is broken at depth by the Tonga-Kermadec Ridge and the East Pacific Rise into separate gyres in the Tasman Sea and the central basin, where it extends nearly to the bottom in the north.

In the central basin the northward abyssal flow is not confined to the western boundary but extends all across the basin, diverted only slightly in the north by the small deep remnant of the anticyclonic gyre.

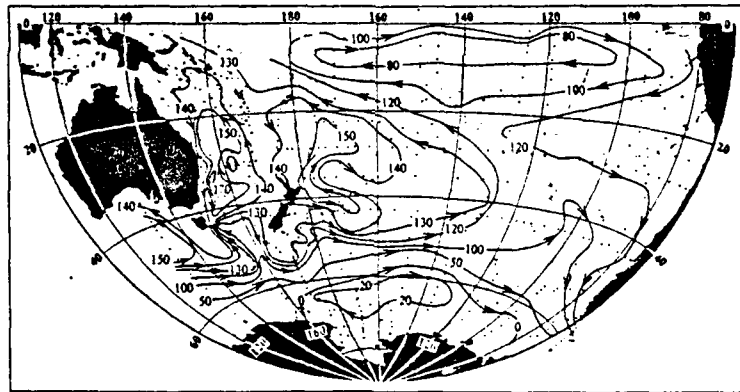


Fig. 73. Transport in units of $10^6 \text{ m}^3 \text{ s}^{-1}$. The shaded area represents depths less than 3500 m. Integration is from Antarctica northward, yielding 135 units along the coast of Australia and 130 units along the coast of South America, with 5 units crossing into the North Pacific

I have worked during the last year toward a similar study of the South Atlantic Ocean, and reported some preliminary results at the Ocean Sciences/ASLO meeting in January 1986 (Reid, 1985).

In addition, Dr. James Swift and I have continued our work on a study of the Norwegian-Greenland Sea, using data from the expedition aboard the Hudson in February-April 1982.

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Paola Malanotte Rizzoli

TOMOGRAPHY OF THE GULF STREAM: NEW INVERSION SCHEMES AND DATA
ASSIMILATION INTO GULF STREAM NUMERICAL MODELS

This project will continue the theoretical work started during the previous project "Gulf Stream Acoustic Tomography: Feasibility Experiment". The tomographic data collected during the feasibility experiment will be used to constrain numerical models of the Gulf Stream system, starting with a quasi-geostrophic baroclinic model. These preliminary assimilation experiments will constitute the preparatory ground work for the assimilation into a primitive equation model of the tomographic data to be collected by 5 tomographic transceivers starting in mid-1987 (Wunsch & Rizzoli, NSF supported proposal). The 5 transceivers will be positioned on 5 current meter moorings, which are part of a bigger array to be deployed by Dr. N. Hogg and the Buoy Group of WHOI for a period of 18 months to 2 years, in the Gulf Stream system after the New England Sea Mountain Chain (centered at 39°N; 54°W). The focus of the work here proposed is upon two main lines of research:

- 1) Assimilation of tomographic as well as traditional data into a numerical model of the Gulf Stream system after the New England Sea Mountain Chain.
- 2) Development of a new inversion scheme suitable for sharp frontal systems like the Gulf Stream.

The approach will be a blend of data analysis and use of inverses to provide data; dynamical experiments with the available, and suitable, numerical models and combination of the models with the data upon limited areas.

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1/1/87 - 12/31/87

Paola Malanotte Rizzoli
Glenn R. Flierl

A THEORETICAL STUDY OF GULF STREAM INSTABILITIES, EDDY PRODUCTION,
EVOLUTION AND INTERACTIONS

This project will continue our work on some important, unresolved questions which have emerged from the experimental evidence accumulated in the past decade in the Gulf Stream and the regions of intense mesoscale activity on either side of the Stream (the Sargasso and Slope Water). We shall focus on the following problems:

- I. The finite amplitude instabilities of the Gulf Stream jet in different parameter ranges (f - versus beta-plane; barotropic; equivalent barotropic, baroclinic models).
- II. Diagnostics and energetics of the radiation field associated with a northern boundary current like the Gulf Stream and its relationship to the jet instabilities of part (I); possible formation of coherent eddies from strong radiation fields.
- III. Evolution and instabilities of isolated vortices as models of isolated, energetic features within the mesoscale eddy field.

Our approach will be a blend of analytical and computer simulation studies. When possible, comparison will be made between the modeling results, the current data base of satellite imagery at MIT and the emerging data base from the planned SYNOP experiment.

The long term objectives are to obtain a fuller dynamical understanding of the Gulf Stream instabilities as the energy source for the mesoscale radiation field and of the importance of mesoscale eddies for modifying the structure of the general circulation and determining the spectrum of large-scale density and velocity fluctuations.

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1/1/87 - 12/31/87

DYNAMICS OF OCEANIC MOTIONS

This contract continues research on the dynamics of oceanic motions: the theory and modelling of fundamental dynamical and energetic processes in the sea and their interactions, and the relationship of theory and modeling to the interpretation, analysis and design of observational data and experiments. Our interests lie in the dynamics and the forecasting of the low frequency variability of ocean currents and in the mid-latitude general circulation. It includes near surface layer/deep current interactions and interactions with coasts, shelves and islands. Research includes studies of the dynamics of (partially) open regions of the ocean, and the relationship of the regional dynamics to the larger scale. A central focus is initialization with real ocean data, data assimilation. The understanding of the local dynamics of the mesoscale and successful assimilation and forecasting are intimately related. The Ocean Predictive Descriptive System (ODPS) components are a dynamical model, a statistical model and observational network. The output of the system is "optimal" field estimation. For practical nowcasts and forecasts these fields can most efficiently exploit available data resources. For scientific purposes, these fields form the best basis for regional process studies, specifically carried out by open regional vorticity and energy dynamical analyses. Real time predictions allow the evolution of experiments and observations efficiently in the dynamically heterogeneous ocean and can substantially accelerate research progress. Specific research topics include: 1. Local Dynamics of the Mesoscale and Interaction with the General Circulation. a) Dynamics of Eddies, Rings and Jets. A general method for local Energy and Vorticity Analysis (EVA) was completed and applied to process studies in the POLYMODE and California Current regions. b) Coupled Surface Boundary Layer (SBL) - Quasigeostrophic (QG) Model Studies. c) Interaction of Deep Ocean Eddy Currents with Coasts and Islands. d) Primitive Equation (PE) Open Ocean Model. e) Embedding Strategies. 2. Data Assimilation and Real Time Nowcasting and Forecasting. a) Multivariate Analysis for Current Systems. b) Initialization and Updating Methods and Strategies. c) Satellite Altimetric Data Assimilation. d) Assimilation Schemes for Lagrangian Data. e) The Gulf Stream Region ODPS. Research of a real time ODPS during the SYNOP experiment. Model stream and ring structures combined with feature locations from satellite IR have resulted in i) successful initialization, ii) realistic simulation including ring formation, and iii) useful forecasts with real time AXBT updates.

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Contract period: 3/01/86 - 2/28/88

GUNNAR I. RODEN

CURRENTS, FRONTS AND EDDIES IN THE CENTRAL ARGENTINE BASIN

Research focused on the thermohaline structure and circulation in the central Argentine Basin, a region influenced by both the Brazil current and the antarctic circumpolar current. The research was based on the cooperative SOUTHERN OCEAN STUDIES field experiment in the SW Atlantic in late 1984. The main objectives were to determine the relationship of the fronts and eddies to these currents and the change of this relationship with depth.

The Brazil current, after leaving the South American coast, returns to subtropical latitudes in a meandering fashion with speeds of 30-50 cm/s. The meanders have a wavelength of 400 km and an amplitude of 200 km. The Brazil and antarctic circumpolar currents do not meet in the central Argentine Basin to form common eastward flow as expressed in classical descriptions, but instead diverge sharply near 42 W. This divergence is suggested also in the path of satellite tracked drifters. The region between the currents is marked by cyclonic and anticyclonic eddies, possibly derived from instabilities of these currents. The Brazil current signatures extend to great depths, in common with other western boundary currents.

In the central Argentine Basin two distinct thermohaline fronts occur, one associated with the Brazil current return flow and the other with the antarctic circumpolar current. The region in between represents a mixing zone, in which waters of both origins are present. The vertical structure of the fronts is complex. Temperature, salinity, and density fronts are not always present simultaneously, nor do they extend to the same depth. Along the poleward boundary of the Brazil current, density fronts are coherent in the upper 3000 m, but temperature and salinity fronts are not. The former vanishes at the interface between the North Atlantic Deep Water and the South Atlantic Intermediate Water and the latter near the core of the intermediate water. Below 3000 m abyssal temperature and salinity fronts are found. Along the sub-antarctic front, the sharp mixed layer horizontal temperature and salinity gradients balance each other in such a way that no density front is formed. The same holds true for eddies of sub-antarctic origin that have drifted northward.

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Contract period: 1 Oct 1985 - 30 Sept 1986

Thomas Rossby

LAGRANGIAN STUDIES OF THE GULF STREAM

This is a study of the Lagrangian properties of fluid motion in the Gulf Stream using acoustically-tracked isopycnal floats. Specifically, through repeated seeding of floats in the center of the current we can i) examine the spatial and temporal properties of the current including the construction of time series of objective maps of the path of the current (for kinematic analysis directly, or for use in numerical model simulation of the current), ii) examine the three-dimensional velocity field and its coupling to the path structure (meandering), and iii) examine mechanisms and pathways of fluid exchange with the surrounding waters including stirring and mixing processes.

Over 40 isopycnal floats have been launched in the center of the current off Cape Hatteras since the summer of 1984. Neutrally buoyant on density surfaces in the main thermocline, $26.8 < \sigma_t < 27.3$, some floats have travelled in excess of 2000 km before leaving the current while others have been ejected within a few hundred km, either way always in a region of strong path curvature. The lateral movement of floats within the current is not stochastic but clearly coupled to the dynamics of curvilinear motion, i.e. upwelling between meander trough and crest and vice versa. This is an important observation for it indicates that there is a high degree of order within the current and that lateral mixing by shear is weak. Stirring is more likely to take place by exchange with waters outside the dynamical path of the current.

Preliminary results from the field program have been published in the Bulletin of the American Meteorological Society (1985) and a description of the RAFOS operating system has been submitted to JAOT (1986).

References

- T. Rossby, A.S. Bower, and P.-T. Shaw, AMS, 1985.
- T. Rossby, D. Dorson, and J. Fontaine, submitted to JAOT, 1986.

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Contract Period: 7/1/83-12/31/86

Thomas Rossby

STUDIES OF FRONTAL MIXING IN THE GULF STREAM

The Gulf Stream can be viewed as a high velocity front under attack by local dynamical processes, some of which may be internal (shear flow instabilities) and others external, such as entrainment, eddy-stream interaction, and bathymetric effects. The scales and detailed structure of these exchange processes appear to be stochastic and limited to scales of 0(10 km) and less, yet the conditions for their onset may be governed by dynamical conditions at the mesoscale (i.e. meandering). Shingle formation, presumably due to upwelling upstream of meander crests is the most common surface expression of cross-frontal exchange. RAFOS floats have revealed corresponding subsurface pathways.

This joint Norwegian-U.S. field program is designed to conduct studies of cross-frontal exchange at sites chosen to emphasize specific processes: i) topographically induced upwelling near the Charleston Bump, ii) entrainment of Shelf Waters off Cape Hatteras, and iii) upwelling and shingle formation in a region of strong anticyclonic curvature.

Using a combination of shipboard instrumentation on the R/V Haakon Mosby from the University of Bergen in September-October 1985, we conducted numerous CTD to-yos between 25m and 150 m depth across the cyclonic shear zone of the Gulf Stream and into the Slope Waters to the north to examine the distributions of T-S-O₂ and Chl-a. A very simple, yet powerful technique for real-time contour-plotting of selected CTD variables was implemented and greatly facilitated the design and execution of the field program. Navigation information was automatically merged into the CTD data stream. XCPs were also taken to determine the corresponding vertical and lateral shear fields.

The data are presently being reduced, edited and calibrated into a working data set. A joint workshop is scheduled for 2 weeks in May, and preliminary results should be ready for presentation by mid-1986.

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Contract Period: 1/1/85-12/31/86

David Rubenstein

**DYNAMICS OF INERTIAL/INTERNAL WAVES
IN THE MIXED LAYER, THERMOCLINE AND IN OCEAN FRONTS**

An increasing body of evidence points toward strong coupling mechanisms between inertial/internal waves in the ocean mixed layer and the thermocline, and interactions with ocean fronts. Background vorticity associated with ocean fronts can strongly affect dynamics in both the surface layer and the ocean interior. My objective is to understand some of these mechanisms, using a theoretical modeling approach, with guidance from recent observations.

During the first year of this project, I developed a new two-dimensional model of internal wave dynamics. I have applied this model to examine the effects of ocean fronts on the variability of near-inertial motions (Rubenstein and Roberts, JPO, Jan. 1986). The results suggest that the mean vorticity associated with a front acts to decrease the spatial scales for inertial motions to comparable to the frontal width, or smaller. Inertial pumping generates internal waves that propagate downward and away from the front. Radiation damping acts to dissipate inertial oscillations in the mixed layer in the vicinity of the front.

I have also begun examining the scattering of inertial waves by bumpy bathymetry. Steady state solutions imply that the bathymetry is capable of completely destroying the large-scale coherence of surface forced waves. Time-dependent solutions show that the coherence degradation takes place over a very long time period (months) after the generation of the waves.

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Contract Period: 3/84-2/86

Richard L. Salmon
George F. Carnevale

Analytic and numerical studies of flow
over ocean bottom-topography

The presence of topography strongly influences geophysical flows. Even in turbulent flows there is on average a "static" component locked to the topography. The significance of this "contour flow" is investigated through a series of numerical simulations of one and two-layer flows. The model topography used in these numerical experiments ranges from highly idealized geometrical forms to accurate representations of actual oceanographic structures including seamount chains and continental shelves. The flow in these simulations is driven in a variety of ways including turbulent decay, dynamically interactive large-scale cross currents, and surface winds. The numerical experiments are compared to the predictions of statistical equilibrium theory, and to nonequilibrium approximations for the evolution of the energy spectrum and the autocorrelation of velocity at different times.

Recent efforts have provided interesting theoretical insights and numerical results. An examination of the predictions of stability theory and statistical equilibrium theory for flow over topography has provided a clarification of the fundamental relationship between these theories. In numerical experiments, we have demonstrated that certain stationary topographic contour flows which are stable in low resolution models, can be replaced at higher resolutions by turbulent flows with a mean contour flow, and the results are sensitive to the choice of enstrophy dissipation. Furthermore, new models are proposed for the investigation of baroclinic flow over topography driven by large-scale interactive flows, and these will be tested in a two layer model.

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Contract period: FY85-FY86

Thomas B. Sanford

OCEAN VARIABILITY AND DYNAMICS

A major theme of our research is the generation, propagation and absorption of inertial waves in the deep sea. The strongest inertial wave generator is a hurricane, and we are analyzing AXCP observations taken in 1984 hurricanes Norbert (Pacific) and Josephine (Atlantic). These observations on the surface mixed layer velocities are being compared with SML velocities from a numerical model by J. Price. In another hurricane related study it was found that velocity profiles at Site D contain inertial motions from Carrie (1971) that are compactly represented in terms of slope modes. Elsewhere, we are investigating the propagation, trapping, enhancement and absorption of inertial waves in steady currents and shears. In a series of recent papers we have published results from studies of inertial waves in a warm core ring, at site D, within a topographically trapped anticyclonic eddy and in a geostrophic front. These studies have revealed the importance of trapping and critical layer processes for near-inertial motions. Moreover, simultaneous measurements of viscous dissipation show a correlation between regions of high dissipation and locations of likely critical layer absorption.

For the remainder of the contract period we intend to complete a paper on the hurricane Norbert and Josephine profiles, continue analysis and publication of our existing data and modify AXCPs for deployment in a N. Pacific storm as part of the Ocean Storms program. Observation of velocity profiles in a fully developed hurricane is a very recent achievement and offers exciting scientific opportunities. Perhaps, the greatest SML velocities occur in these storms. The modifications to the AXCPs for Ocean Storms are to slow the probe fall rate to 1 m/s while maintaining the rotation rate at several Hz. Such an AXCP would provide velocity profiles that are better suited for the separation of surface waves from steady or inertial velocities and vertical shear. Finally, we are working with a new vorticity sensor. Experiments and analysis are being conducted on its use as a detector for pancake eddies (vortical modes) in the deep ocean and for surface wind stress.

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1 October 1985 - 30 September 1987

Raymond W. Schmitt
John M. Toole

FINE- AND MICROSTRUCTURE STUDIES OF AN UPPER OCEAN FRONT

An ONR sponsored experiment to study atmospheric and oceanic dynamics near a sea-surface temperature front is currently underway. The Frontal Air-Sea Interaction Experiment (FASINEX) includes a six-month moored study (January-July, 1986) and an intensive two-ship, multi-aircraft program during February-March, 1986. The present program is a component of this field effort aboard the R/V Endeavor. Vertical profiles of velocity, temperature, salinity, and microscale temperature, conductivity, and shear fluctuations will be collected with a new free fall profiler. A companion project supported by NSF will obtain upper ocean velocity data using a ship mounted acoustic-Doppler profiler and temperature/salinity data from a wire lowered CTD.

A goal of the oceanographic component of FASINEX is to document the structure of an upper ocean front and to discover if the oceanic response to atmospheric forcing is sensitive to the presence of a front. Near inertial frequency internal waves are often observed in response to wind forcing events. Previous studies have documented inertial wave trapping in zones of negative relative vorticity as are found on the warm side of a northern hemisphere front. We thus anticipate observing significant differences in the inertial response on either side of the FASINEX front. Of significance are the zones of low Richardson Number associated with trapped inertial waves. Significant mixing could be associated with these features. If so, oceanic fronts are important sites of mixing in the ocean interior. This idea will be tested in FASINEX.

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Contract Period: 1 October 1985 - 30 September 1986

William J. Schmitz, Jr.

LOW-FREQUENCY OCEAN CIRCULATION

The main goal of this project and of the principal investigator is to describe the properties of the low-frequency ocean circulation, with particular emphasis on the relation between eddies and mean flow. A secondary objective is a comparison of the data base with results from numerical models.

Several long-term deployments of arrays of moored instruments in the North Atlantic were completed by 1977 and a similar geographical exploration of the North Pacific was initiated in 1980. A major new experiment in the western North Pacific began in the fall of 1983, extending coverage zonally from 152°E across the North Pacific at mid-latitudes. This moored array was recovered for the final time in the fall of 1985. The priority for this project is and will be publication on the new North Pacific data base, including comparisons with the North Atlantic.

Model-data intercomparisons were started with regional numerical experiments in 1978 and expanded to gyre-scale runs in idealized geometry beginning in 1979. The regional numerical model available tended to do a decent job in the MODE area for the period range (nominal) of 50 to 150 days, but not otherwise. The two-layer gyre-scale eddy-resolving models developed by W. R. Holland at NCAR and examined next tended to reproduce approximately many of the observed features of the North Atlantic eddy field, with the main question becoming the zonal penetration scale from the west coast.

Another intercomparison of observation with Holland's models was initiated in 1984. The zonal scale question was resolved, and eight-layer runs were examined. In 1985, a major new intercomparison involving these 8-layer numerical experiments was completed. The results are quite favorable for two particular runs, one relevant to the North Pacific and another for the North Atlantic. The models under evaluation are forced by a steady wind, with the eddy field being the result of instability processes. The intercomparison results suggest that this mechanism is dominant in the western segment of northern hemisphere subtropical gyres, with the models even being able to reproduce temporal spectra reasonably well.

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January 1, 1986 - December 31, 1987

Dr. Friedrich Schott

WESTERN BOUNDARY CURRENTS IN THE INDIAN OCEAN

Mogred arrays were deployed in the East Madagascar current at 23°S , in the North Madagascar Current at 12° and in the Somali Current on the equator from October 1984 to September 1985. The Somali Current array was redeployed for a second year, until October 1986, including a buoy-mounted acoustic Doppler profiler (ADCP) for near-surface profiling. Five ship surveys of the boundary current systems were carried out with the French R/V MARION DUFRESNE, using 115 kHz ADCP, XBT's, CTD (2 cruises). Deep CTD sections in April 1985 revealed a southward deep circulation in the western Somali Basin (Fieux, Schott, Swallow, Deep-Sea Res., in press) opposite from what was found in August 1964 during the IIOE. The currents east of Madagascar were found to have no significant seasonal cycle, although the wind forcing over the South Equatorial Current varies seasonally by about 50%. Horizontal eddy kinetic energy had similar magnitude and baroclinicity as found in the subtropical North Atlantic at similar latitudes. Current structure in the equatorial Somali Current during the winter monsoon differs considerably from what was concluded from earlier observations north of the equator. The southward flow near the surface is only about 100 m deep, underneath in the depth range 100-600 m undercurrent flows northward. The observations are analyzed in conjunction with data from a high resolution numerical model (G. Philander) and good agreement is found in the top 500 m, in the equatorial regime.

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October 1, 1984 - September 30 1986

Robert L. Smith

OPTOMA CURRENT MEASUREMENTS

As an adjunct to the Naval Postgraduate School/Harvard OPTOMA (Ocean Prediction Through Observation, Modeling and Analysis) Program, three deep-sea subsurface moorings were deployed 100-200 km off Northern California ($38^{\circ}39'N$; $124^{\circ}-126^{\circ}W$) from September 1984 to July 1985. The triad of moorings had a mutual separation of 100 km and were in water 3400-4400 m deep. On each mooring there were 5 Aanderaa current meters which recorded hourly speed, direction and temperature at the nominal depths of 150 m, 350 m, 800 m, 1250 m below the surface and 200 m above the bottom. A comprehensive data report is being prepared; a preliminary report was given at the Ocean Sciences Meeting in New Orleans in January 1986.

The horizontal coherence between the current measurements at the separation of 100 km was nil. This is not surprising; the radius of deformation for the first baroclinic mode (computed from CTD casts to the bottom) was 0(25 km). The array was designed as a test of the OPTOMA model and to determine the barotropic component of the flow. For periods of 10 days and longer, there was very high vertical rotary coherence between the two uppermost current velocity records on each mooring. The first complex EOF mode, based on the 5 current meter vertical array, contains 90% of the subtidal energy. The shape of the first two EOF modes are similar, respectively, to the first two dynamical modes computed from the CTD data.

Surprisingly, the alongshore convergence at 150 and 350 m of the flow, calculated from the two array elements deployed nearer shore with a 100 km alongshore separation, is significantly correlated with the temperature and the normal component of the velocity at the offshore mooring. The alongshore convergence leads the offshore component of the flow by about 6 days and the temperature by about 20 days. It seems that the AVHRR satellite temperature field may be related to the flow field as deep as 350 m. We are continuing the analysis of the current meter measurements in conjunction with Drs. Mooers and Rienecker at NPS, using both hydrographic and satellite data.

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1 November 1985 - 31 October 1986

John L. Spiesberger
Robert C. Spindel

ACOUSTIC TOMOGRAPHY IN THE GULF STREAM: A FEASIBILITY EXPERIMENT

In the Fall of 1984, an acoustic tomography experiment was conducted near the Gulf Stream. A bottom-mounted source (400 Hz, 10 ms resolution, 176 dB re 1 μ Pa @ 1 yd) transmitted signals along steep ray paths to three bottom-mounted receivers at ranges from 20 to 50 km. The observed acoustic rays were steep (about 20° from the horizontal) and reflected from the rough surface and bottom. The rays were observed to have large signal-to-noise ratios (20 to 40 dB) even during the onset of hurricane conditions.

The geophysical inverse problem is very nonlinear when non-reflecting ray paths are used in the Gulf Stream region. It is difficult to interpret results from nonlinear inversions. However, the inverse problem is very linear when reflecting ray paths are used, and results can be interpreted using standard techniques. This experiment demonstrated the feasibility of using tomography to investigate Gulf Stream variability.

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Contract Period
1 Apr 1984 to 30 Sept 1986

Timothy Stanton
Edward Thornton

DENSITY, SHEAR AND TURBULENCE MEASUREMENTS
IN THE UPPER OCEAN

Temperature, salinity and velocity profile time series were acquired around a 5km box centered on FLIP during MILDEX. The CTD and acoustic doppler current profiler data have been combined to produce density, N^2 and shear Richardson number profiles which map entrainment and stability changes in the mixed layer in the vicinity of FLIP over a ten day period. The gradients of temperature and density across the measurement box are being used to identify large scale features propagating through the area. The spatial distribution of low stability layers are being determined from the Richardson number profiles, and their temporal evolution is being compared with the local atmospheric forcing and the deep inertial wave measurements made from FLIP.

A series of acoustic doppler shear profiles and microstructure measurements were made from the R/S DOLPHIN in conjunction with turbulence measurements made by Tom Osborn during October 1984. Shear profiles with a 1m resolution were measured from the bow of the submarine using a 1.2 MHz upward-looking acoustic doppler profiler. A concurrent towed CTD and doppler profiler survey was made from the R/V ACANIA during a period when there was high near-inertial wave activity. The role of the internal wave shear on the observed mixing rates is being examined.

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JAMES H. SWIFT

A STUDY OF THE NORTHERN HEMISPHERE DEEP CIRCULATION

The scientific objectives focus upon the formation and circulation of the deep water masses of the northern hemisphere, with special emphasis upon the Arctic Ocean and its peripheral seas. Previous results showed that the Arctic Ocean deep waters are efficiently ventilated from the peripheral shelf seas, making the Arctic Ocean an effective contributor to the deep World Ocean. In another study tracer data were used to study the connection between the Greenland Sea and North Atlantic via surface inflow to the Greenland Sea and outflow to the North Atlantic of much denser water. New results on the origin of the deep water of the Norwegian Sea are in draft form.

Other work includes an analysis of the Greenland Sea circulation; a volumetric θ -S census of the Greenland Sea; an extension of recent North Atlantic analyses southward to 20°S ; an examination of new hydrographic data from Fram Strait to determine the origin and circulation of the waters; and an examination of the North Pacific deep circulation.

Hydrographic sampling at the Arctic Internal Waves Experiment site was completed successfully and a final data report will soon be published. This work included surface-to-bottom sampling for T, S, O_2 , and nutrients, and collection of geochemical samples (tritium, C-14, Cs-137, and Sr-90). These data have recently been used to examine the Arctic Ocean contribution to the outflow through Fram Strait.

An expedition to the northern Barents Sea slope and deep Nansen Basin of the Arctic Ocean on the R/V Polarstern has been proposed and scheduled for 7/7 - 9/15/1987. Measurements proposed for this contract include sampling for temperature, salinity, oxygen, and nutrients to complement the CTD program. This interfaces with an integrated program of tracer and velocity measurements. The objectives are to determine the characteristics of Nansen Basin and adjacent slope waters from the ice boundary to a few meters above the sea floor, and to identify principal boundary currents and determine their strength and structure.

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Contract Period 10/1/85 - 9/30/87

Lynne D. Talley

MESOSCALE VARIABILITY AND INSTABILITIES OF THE KUROSHIO
EXTENSION

The primary source of eddy variability in the western North Pacific Ocean is the Kuroshio Extension, undoubtedly through its instabilities. The principal objectives of the research are (1) to describe the nature of variability in the western Pacific, using the Transpac XBT data as a primary data source, (2) to extend a theoretical model of linear instabilities to finite amplitude and to more complicated flows which better correspond with the mean structure of the Kuroshio Extension, and (3) to examine the growth of such instabilities in numerical models. The instabilities mentioned in the second and third objectives can be trapped to the Kuroshio Extension or can radiate energy far north and south of the Current. Very little is known about radiating instabilities (which depend on the existence of Rossby waves in the ocean north and south of the Current) and the latter two objectives are focused entirely on understanding them.

Warren White and I have been analyzing the Transpac XBT data in the mid-latitude North Pacific. We have found that the dominant wavelength is larger in the eastern Pacific than in the western and occurs at lower frequency. A significant shift in spectral peaks from north to south is not observed. Difficulties with using spectral methods to recover information about the North Pacific eddy field arise from patchy sampling and inhomogeneities in eddy energy and scales. The spectra are generally consistent with Rossby wave propagation in a slow, mean, eastward flow. We have found that the wind field, which can account for forcing of the spectra in the eastern Pacific, does not account for the spectra of the western Pacific. Time and space sampling in the data set in the western Pacific is not adequate to estimate energy transfers so we are turning to other data sources to better determine the role of instability of the Kuroshio Extension.

Radiating instabilities have been examined in barotropic and baroclinic models of currents like the Kuroshio Extension. A study of the instabilities of a jet with countercurrents, which models the Gulf Stream and Kuroshio was recently completed; the addition of westward counterflow allowed the otherwise eastward jet to radiate energy to the far field. A study of the nonlinear evolution of radiating barotropic instability is underway and I am collaborating with Dale Haidvogel (NCAR) in a study of the conclusion of radiating instabilities in numerical models.

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10/01/85 - 09/30/86

Eugene A. Terray

TURBULENCE MEASUREMENTS BENEATH WIND WAVES

We are developing a three-axis, range-gated, Coherent Doppler Sonar (CODS) to measure the vertical structure and statistical characteristics of small-scale turbulence in the upper mixed layer. Our purpose is to determine the flux of turbulent energy and momentum driven by the local wind stress, and to assess the relative importance of production, transport and dissipation in the overall turbulence budget.

Although the direct application of pulse-coherent Doppler sonar to high frequency (10 Hz) velocity measurements is limited by the inverse relation between maximum unambiguous range and velocity inherent in such systems, it is known that the use of coded signals can redistribute this ambiguity in range-velocity space. To investigate the utility of this approach, we constructed a single-axis prototype instrument, and demonstrated that a simple bi-phase code would enhance the useful range of the device by a factor of order 5. Since the purpose of coding is to spread the unwanted signal energy throughout the spectrum, we have also evaluated various Doppler estimation algorithms with respect to their noise sensitivity, and have concluded that a spectral peak-picking technique offers the best performance. These results are being prepared for publication, and a field instrument employing pulse coding is under construction.

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John M. Toole

HYDROGRAPHIC OBSERVATIONS IN THE AGULHAS RETROFLECTION AREA

The Agulhas, the western boundary current of the South Indian Ocean, typically exhibits a sharp reversal of direction south of the African continent. This so called Agulhas Retroflection is one focus of the ONR Southern Ocean Initiative. In February/March 1985, in coordination with the deployment of a moored current meter array for J. Luyten, a hydrographic survey of the Agulhas Current, the Retroflection Zone and the Agulhas return current was performed. A total of 92 CTD/O₂ casts were collected to the ocean bottom with rosette water sample analysis of salinity and dissolved oxygen. The data have been calibrated and analysis begun. The principal investigator is being assisted in this effort by Sara Bennett, a doctoral candidate in the MIT/WHOI Joint Program, who is focussing her research on the Agulhas. Initial results, reported at the fall AGU meeting, deal with the path of the current during the survey period.

We are also interested in the circulation of South Indian Subantarctic Mode Water (SAMW) in this area, and the extent to which it is confined within the retroflection and retroflection eddies, and evidence of modification by South Atlantic and Circumpolar influences. The core layer defining the SAMW is a weak vertical minimum in potential vorticity(q)/static stability. A paper which explores the effects of reference pressure choice on the q field, in particular weak features of the q field such as the South Indian SAMW, is in preparation.

Other topics to be considered using these data include:

- ° A comparison of the Agulhas and Gulf Stream systems
- ° Confluence and interleaving at the AAIW salinity minimum
- ° Survey-to-survey comparisons using A. Gordon's 1983 Agulhas Retroflection Cruise hydrographic data

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Dennis B. Trizna

SHIPBOARD MARINE RADAR ESTIMATES
OF WIND STRESS AND MOMENTUM FLUX
DURING FASINEX

The objectives of our FASINEX participation are: (1) to gain a better understanding of the dependence of the scattering mechanisms responsible for low grazing angle sea scatter statistics on wind stress and momentum flux; (2) to determine the effects on the marine radar sea scatter due to the sea surface temperature change associated with the thermal front, in concert with similar measurements made by the airborne active and passive remote sensors.

During the FASINEX experiment, we are utilizing the marine radars on board the participating ships, the Knorr and the Oceanus, for the measurement of low grazing angle sea scatter. Based upon preliminary measurements made aboard NOAA ships, a correlation was shown to exist between parameters of the cumulative distribution function of the normalized sea surface radar cross section (NRCS) and wind speed under equilibrium conditions. This type of measurement appears to distinguish between sources of scatter due to small scale surface features generated by the wind, such as capillary waves, and discontinuous surface features generated by hydrodynamic interactions, such as wave breaking.

Although some hardware difficulties were encountered, a sizable amount of X- and S-band radar data were collected aboard the Knorr during the deployment of the buoy array. The data acquisition system was successfully deployed aboard the Oceanus and X-band data are currently being collected. Although first-lock processing indicates good quality data, radar calibration remains to be done before data analysis can proceed.

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1 Jan 86 - 30 Sept 86

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Abstract of work supported by current ONR contract:

The investigation of internal wave interaction with mesoscale shears is complete and published (J. Phys. Oceanog. 15, 1286-1311, 1985). As a result of this work it was concluded that mesoscale currents represent a significant source of energy for the internal wave field - $\approx 10^{-3}$ w/m². Horizontal and vertical eddy viscosities were calculated to be 40 and 5×10^{-3} m²/s.

Also complete and in process of publication (in the J. of Geophys. Res.) is an analysis of the persistence of surface wave patterns, such as those of Kelvin wakes. Air-sea interaction and hydrodynamic non-linearities represent the principal mechanisms for destroying a surface wave pattern. Numerical results are presented.

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D. Randolph Watts

THE DYNAMICS OF GULF STREAM VARIABILITY

In the region northeast of Cape Hatteras, NC, the Gulf Stream path meanders, typically with amplitude increasing downstream. It ranges throughout an envelope that grows to several times the width of the current itself and frequently interacts with rings and eddies. Previous observational and theoretical modeling studies have raised questions regarding the fundamental dynamical and energy balances governing the meandering.

During the past funding period we have been collaborating with Dr. John Bane (UNC) in observational studies of the structure and energetics of Gulf Stream fluctuations. A large data set was obtained from an array of inverted echo sounders and current meter moorings deployed just downstream of Cape Hatteras in a region of rapid growth of meanders. The goal of this study was to characterize the full x,y,z, and t structure of the fluctuations and to determine the relative importance of baroclinic and barotropic instability processes in supplying energy to them.

A large coordinated research effort (SYNOP) is being planned to understand and model these highly energetic mesoscale fluctuations in the Gulf Stream from Cape Hatteras to the Grand Banks. We are preparing to conduct a pilot experiment at Cape Hatteras to develop and verify efficient new techniques that continuously determine "inlet conditions" for the flow entering the SYNOP study area. Among the parameters to be monitored are the position, angle and curvature of the path, the cross-stream structure of the thermocline (and the associated variations in the baroclinic velocity field), and the volume transport (which has been observed to vary by nearly a factor of two from one month to the next). In particular, we are developing an acoustic method to monitor the volume transport, with an engineering test scheduled for June/July, 1986. A pilot array involving acoustic transport meters and inverted echo sounders, designed to study all the above parameters will be deployed for about 3 months, starting November, 1986.

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Georges Weatherly

STUDIES OF ABYSSAL FLOWS AND THE BOTTOM BOUNDARY LAYER
IN HEBBLE

Near bottom current, temperature and optical transmissivity records I obtained in water depth 4830 m at the HEBBLE (High Energy Benthic Boundary Layer Experiment) site (40.5N, 82.5W) are being analyzed. These include a 3.75 year continuous velocity and temperature record, and two sets of bottom boundary layer observations spanning this layer over a fourteen month period. The long continuous record (Ianov et al., JGR, 1986) statistically confirms what we previously descriptively inferred, namely, that strong abyssal flows (storms) are more likely when the surface Gulf Stream (as inferred from satellites) is not overhead but far to the south. The bottom boundary layer observations confirm its Ekman layer-like structure, but also indicate unsuspected structure in the turbulent fluctuations.

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HORIZONTAL VARIABILITY IN AIR-SEA INTERACTION

In order to better understand the role of horizontal variability in air-sea interaction, a cooperative field experiment was conducted in the first six months of 1986. The working area, between 25 and 28 degrees N and between 68 and 71 degrees W, was chosen in order to include relatively strong and persistent oceanic fronts. The oceanic fronts were thus the source of horizontal variability for investigations of both the upper ocean and lower atmosphere and of the interaction between the two. Both oceanographers and meteorologists participated in this Frontal Air-Sea Interaction Experiment (FASINEX); and a combination of satellite remote sensing, moored, shipboard, and aircraft techniques were used (as described in the other summaries by FASINEX principal investigators included in this volume).

This investigator participated in the field work on RV Knorr and RV Oceanus. In January RV Knorr used both satellite AVHRR imagery (obtained by Peter Cornillon, URI) and XBT surveys to locate a front with a 2 degree C temperature jump. An array of five surface moorings (Weller, WHOI) and four Profiling Current Meters (PCM) moorings (Eriksen, MIT) was set across that front. The mooring work was followed by CTD profiling and Real Time Profiler (RTP) profiling of velocity, conductivity, and depth across the front, and a Vertical Current Meter (VCM) experiment at the front.

Oceanus (Weller, Pollard, Regier, and Davidson), accompanied by Endeavor (Schmitt, Toole, Oakey, and Large), returned to the FASINEX area in early February. The 2 degree C front was still present, to the north of the moored array. Oceanus and Endeavor studied the frontal features in the area and also worked around the moored array. On some days aircraft (including the NRL P3, NCAR Electra, NOAA P3, NASA P3, NASA C130, and NASA Electra) carried out boundary layer and remote sensing studies with support from the ships. Oceanus' work included SeaSoar and Doppler velocity profiler surveys of the density and velocity fields, combined VCM and radio tracked drifter (Davis and Regier, SIO) experiments to investigate the convergent nature of the velocity field at and near the fronts, Real Time Profiling of the velocity structure very near the surface, CTD profiling, and meteorological sampling, both continuously while underway and, on special days, in support of the aircraft program. Oceanus and Endeavor returned to Woods Hole in mid-March after completing their joint study of the FASINEX area.

In June-July Knorr returned to the FASINEX site for final field work and recovery of the eleven FASINEX moorings, including two deployed in October 1984 (Ken Brink, WHOI) as well as the nine deployed in January 1986. The remainder of the 1986 was spent on the analysis of the data collected during the field work.

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Robert A. Weller and James F. Price

THE STRUCTURE AND DYNAMICS OF FLOW WITHIN THE SURFACE MIXED LAYER

We have acquired high resolution upper ocean and meteorological data sets from the MILDEX and LOTUS programs. These data sets document the upper ocean velocity and density response to atmospheric forcing, and provide the impetus to develop and test models of the upper ocean.

MILDEX data made from R/P FLIP provide a detailed look at the upper ocean vertical shear. During periods of neutral static stability (night time), the shear is often very small, and not well-correlated to the surface stress. At times however, we see intermittent, and strong shears that appear to be associated with organized, three-dimensional flow structures like Langmuir cells. During periods of stable stratification we see much stronger vertical shear that is well correlated with surface stress. Under these stably stratified conditions we do not see the strong intermittence noted above.

LOTUS data provide a very extensive record of the diurnal thermal cycle. We have used these data to test model functions which relate the atmospheric forcing directly to the heating and wind stress. These model functions can be used to forecast the oceanic diurnal cycle response given standard meteorological forecast data, or to hindcast the diurnal sea surface temperature (SST) response seen in satellite imagery.

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January 1, 1986 - December 31, 1987

Warren B. White

MESOSCALE VARIABILITY IN THE THERMAL STRUCTURE OF THE KUROSHIO EXTENSION IN THE WESTERN MID-LATITUDE NORTH PACIFIC

During the past two years, two manuscripts have been completed, both in collaboration with other individuals. The manuscript in collaboration with Nouhai He is phenomenological in nature, describing the time/space evolution of mesoscale anomalies in 300 m temperature in the Kuroshio Extension for the 4-year period 1979-1982. It establishes that large changes in mesoscale anomaly patterns, at zonal wavelengths of 500-1000 km, occur primarily in winter near bottom bathymetry features; i.e., over the Shatsky Rise located at 160°E and over the continental slope of Japan at 142°E. This strongly suggests that mesoscale variability in the Kuroshio Extension is invigorated by wind-driven barotropic meridional motion, operating most strongly each winter season, intensified by bottom bathymetry gradients. The manuscript in collaboration with Lynne Talley is statistical in nature, describing the wavenumber/frequency spectra of mesoscale variability (i.e., corresponding to zonal wavelengths of 500-1000 km) in 300 m temperature in the mid-latitude North Pacific for the 8-year period 1976-1984. In the central and eastern mid-latitude ocean, these spectra are shown to have local maxima in spectral energy density at periods of 2-3 years, extending to higher frequency on the dispersion curve of theoretical baroclinic Rossby waves. In the western mid-latitude ocean, this is also shown to have been true, but with local maxima in spectral energy density occurring at higher frequencies corresponding to periods of 3-10 months, extending to lower frequencies on the dispersion curve of theoretical Rossby waves. North of the Kuroshio Extension we found at low wavenumber the phase of the waves directed toward the south, which according to Rossby wave dynamics is associated with energy radiating northward away from the axis of the current.

An additional study was conducted in collaboration with Bill Holland (NOAF). It was concerned with the numerical simulation of large-scale and mesoscale anomalies in the western mid-latitude North Pacific, for the 8-year period 1977-1984, using a quasi-geostrophic numerical model driven by realistic winds for the 20-year period 1965-1985. This model has been run for two years already (1979-1981) and has achieved intensified winter response in the vicinity of the continental slope of Japan, the Shatsky Rise, and the Emperor Seamounts.

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9/30/84-9/30/86

Carl Wunsch
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OBSERVATIONS OF THE GULF STREAM SYSTEM BY RECIPROCAL
ACOUSTIC TOMOGRAPHY

This is a new proposal to begin the exploitation of the new technology of reciprocal tomography for the scientific purpose of understanding the highly energetic region within and near the Gulf Stream. It specifically requests funding to cover the incremental expense of adding 5 tomographic instruments to a current meter array proposed independently to CDR by N. Hogg. Instrument acquisition is being funded by the NSF, and the concurrent manpower costs should be covered through the Secretary of the Navy chair.

1/1/86 - 12/31/86

W.R. Young

Ageostrophic Instability in the Ocean

Large scale flows in the ocean frequently violate the approximations used to justify quasigeostrophy. One striking example, evident in satellite photographs, is the meandering Gulf Stream front. This feature might be idealized as a "surfacing" isopycnal. But in this case the quasigeostrophic approximation, which assumes that density layers are almost flat, is inappropriate. The present project is an attempt to understand the new instabilities and eddy-mean flow interactions which occur in these ageostrophic flows.

This is a collaborative effort with G.R. Ierley from Michigan Technological University. We've completed the formulation of the linearized stability problem in a two-layer fluid on the β -plane. The geostrophic approximation has been avoided but may have to be reintroduced later in order to asymptotically understand our numerical results. Another new result is a multi-layer generalization of Ripa's theorem (J. Fluid Mech., 1983).

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Norman J. Zabusky

Evolving Nonlinear Jets and Rings and Models of Gulf Stream Variability

Work continued on all fronts. The moment model for 2D vortex dynamics¹ has been accepted and the galley was recently returned to the editors. The axisymmetrization and gradient intensification paper² has been accepted tentatively subject to revisions which are being made. The work on symmetric merger via the moment model has been generalized to include dissipation. The work is being written up and we expect to submit a publication before the summer. The work with Flierl and Rizzoli at M.I.T. on jets in a one level β -plane is in the final process of revision. We expect to submit this paper to the Journal of Physical Oceanography by the end of April. We have observed many novel features of one-level β -plane jets which are summarized in a β vs diagram.

Dr. I. L. Chern visited (8/16 - 11/15/86) and made progress on the motion of an isolated vortex entity on the β -plane. This work ceased when he departed. We are seeking to hire a new post-doctoral employee who will continue this work. The work with S. Lund on acoustic radiation effects on vortex dynamics was summarized in a brief letter submitted to Physical Review Letters.⁴ Review papers on the use of computers in fluid dynamics³ and on computational vortex dynamics⁵ have been published or are in press, respectively.

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Refereed publications resulting from support
from the ONR Physical Oceanography Program (Code 1122P0) from FY85.

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KEY TO PHYSICAL OCEANOGRAPHY FIELD PROGRAMS

<u>KEY/LOCATION</u>	<u>PROJECT</u>	<u>PRINCIPAL INVESTIGATORS</u>
1. Western North Atlantic	Gulf Stream System	Various
2. New England Seamounts	Eddy-Mean Interactions	Rege, Rossby, Weatherly
3. Newfoundland Basin	SOFAR Eddy Dynamics	Evens
4. Eastern North Pacific	Thermocline Dynamics	Leffler
5. California Region	Frontal Studies HILDEX-Mixed Layer Dynamics OUTCUT-Mesoscale Ocean Prediction PATDEX-Mixing Dynamics	Leffler, Cox Rienecker, Keller, et al. Roberts, Robinson, Smith Dunstan, Gregg, Wyrt, Rienecker
6. Brazil-Argentina	Brazil-Falkland Currents	Pratt, Evans, Donnell, Gordon, Olson, McCarthy, Rienecker
7. Agulhas-Benguela	Retroflection	Gordon, Rienecker, Gordon, Luyten, Olson, Toole
8. Southwest Indian	Boundary Currents	Various
9. SE of Portugal	CASINEX	Weller, et al.
10. NE Pacific	OCEAN STORMS-Air/Sea-Strong Forcing	Pratt, et al.
11. Pacific Sea	AINEX-Arctic Internal Wave Experiment	Leffler, et al.

Location of major observational field for 1991



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